BBC RD 1990/2

Research Department Report

HDTV - A CHANCE TO ENHANCE TELEVISION COLORIMETRY

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THE BRITISH BROADCASTING CORPORATION

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Summary

The development of a new High Definition Television system for use within Europe has provided a unique opportunity to depart from standard television colorimetry and coding which has been used worldwide since colour television began.

All television systems in operation at present use coding systems which allow substantial proportions of the perceived luminance to travel via narrow band colouring channels, thus reducing luminance detail in coloured areas. This is known as the 'failure of constant luminance'. Also, the gamut of colours reproducible by existing television systems and equipment does not do justice to saturated colours encountered in real life.

A new system has been devised which greatly expands the colour gamut that can be reproduced, and uses constant-luminance coding to avoid loss of detail in coloured areas. This has been achieved without compromising compatibility with the existing television system; the proposed system produces signals which can be decoded by a conventional receiver while still producing satisfactory colour reproduction and sharpness. The enlarged colour gamut of the proposed system will allow future displays to provide continuing improvements in colour performance as new types of display (e.g. laser projectors) are developed with increasingly saturated display primaries.

The constant-luminance decoding receiver is necessarily more complex than a conventional receiver, and may not be achievable without resort to digital processing in the domestic receiver. Studio monitoring using constant-luminance decoding could also be prohibitive in both cost and complexity. To overcome both of these problems, a modified form of standard decoder has been developed; it almost completely removes the residual colour errors due to compatible decoding while retaining the colour sharpness advantage of constant-luminance coding.

Issued under the Authority of

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Research Department, Engineering Division,
BRITISH BROADCASTING CORPORATION

(PH-298)

1990

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1. INTRODUCTION

This Report describes the mathematical and subjective processes involved in the development of improved colour coding methods for a new HDTV transmission system. The work to be described was carried out at the BBC as part of activities concerned with EBU Specialist Group G4/col and the Eureka 95 project, and involved close collaboration with other organisations particularly within Eureka.

At the outset, two requirements were felt desirable for a new television system, namely a wider colour gamut than is achievable with the existing colour primaries, and adherence to the constant-luminance principle. It was also felt that these improvements should be made without sacrificing compatibility with existing receivers.

A wider colour gamut is desirable to increase the fidelity of colour reproduction at a time when fashionable fabric colour saturations are increasing noticeably. Although the traditional shadow mask display tube will remain the prime display device for many years, new displays are becoming available which are not limited by phosphor light emitters. Some possibilities, for example, are lasers, liquid crystal matrices and electro-luminescent panels. Designing a system with a wider gamut would allow for continual improvements in colour fidelity as display devices develop, in effect 'future-proofing' the system.

Adherence to the constant-luminance principle would ensure maximum sharpness in coloured detail; it seems inappropriate to incorporate in a new system described as 'High Definition' a colour coding system with less than optimum resolution when a better alternative is available (the workings of a constant-luminance system are described later). Previous attempts[1,2,3] to introduce the benefits of constant-luminance coding have failed because of the increased complexity of the receiver, but with digital processing becoming available for domestic receivers this is no longer the problem it was, and will almost certainly be feasible in the near future.

Compatibility requirements might, at first sight, preclude any attempt to alter the mathematics of colour analysis and coding; however the conflicting requirements can all be accommodated provided that some residual colour reproduction errors can be tolerated in the compatible receiver. It is shown below that wide gamut primaries and constant-luminance coding can be used together to produce a colour coding system which is compatible with conventional coding to a remarkable degree. Also, a simple modification to compatible displays requiring enhanced performance, such as might be used in studio monitors, is described which can further reduce these residual errors to a point where they are hardly perceptible.

For a full understanding of the mathematical processes involved in this work, the reader is first introduced to the colorimetric equations of conventional and constant-luminance coding before describing the proposed system.

2. COLOUR TELEVISION DESIGN CONSIDERATIONS

This section describes the colorimetric properties of television in some detail; the experienced reader may wish to omit this and go on to the next section.

It is natural to wish to find ways of reducing the transmission costs of television. Traditionally, colour information is transmitted as a luminance signal and two colour-difference signals, organised so that the colour-difference signals are both zero for the balance colour (white), thus ensuring compatibility with monochrome displays. The means of carrying these signals is not relevant to the context of this Report.

The precise formulation of the signals requires detailed knowledge of the workings of the human visual system in order to minimise the transmission bandwidth in the most cost-effective way; the following sub-sections outline some aspects of colour vision, and the colorimetric design of conventional television systems.

2.1 Colour vision receptors

The colour sensors of the eye are the cone cells, so-called because of their shape. They are distributed densely over the central area of the retina, but much less so elsewhere. The other sensor organs of the retina, the rod cells, respond only to luminance and are effective at very low light levels where the cone cells give little or no response; they are particularly effective in moonlit conditions. There are no rod cells in the macula, the central 2° area of the retina. Thus colour vision operates well only at sensible lighting levels, and only over the central part of the field of vision, about 30°, with optimal performance over the central 2°.

The cone cells are of three types, with pigments which have spectral absorbencies in the red, green and blue regions respectively. According to Walraven and Bouman[4] the population densities of these cells are in the ratios of 40:20:1. A simple bandwidth saving technique as suggested by Hunt[5] and others becomes obvious; since there are very few blue sensors any blue image need only be presented to the eye in low resolution.

It is worth examining the retinal processing as a colour coding system. Mollon[6] has presented a plausible explanation. Note that the eye responds logarithmically to light, thus all the colour processing is done on non-linear signals. The CIE[7] formulation for this transfer characteristic approximates to a power law of 0.43. From the three sensor types, a luminance signal is formed by addition:

$$L' = R' + G'/2 + B'/40 \qquad (2.1)$$

where the factors 2 and 40 derive from the cell abundancies and the prime indicates non-linear processing. Three colour differences are formed:

$$C_1' = R'-G', \quad C_2' = G'-B', \quad C_3' = B'-R' \qquad (2.2)$$

These have redundancy since $C_1' + C_2' + C_3' = 0$, so another colour difference is formed:

$$\begin{aligned} C_4' = C_3' - C_2' &= (B' - R') - (G' - B') \\ &= 2B' - (R' + G') \end{aligned} \qquad (2.3)$$

The signals L', C_1' and C_4' are transmitted to the brain as rate-modulated pulse trains, with repetition rates rising to about 400 Hz.

Note that blue contributes very little to luminance. Also the optical lens has significant chromatic aberrations and focuses only in the yellow/green range; therefore the blue image is not only seen in lower resolution, it is not even in focus on the retina.

2.2 Colour transitions

How does the eye see colour transitions? This question was investigated objectively by Hacking[8] who effectively measured the required bandwidth for undistorted colour transitions. His measurements were done optically, using a high resolution luminance change with an adjustable resolution colour change in register with it. The results were related numerically to a hypothetical 3 MHz, 405-line colour television system, but they are still relevant today if they are used as percentages of luminance bandwidth. Conventional television coding systems tend to produce distortions when reproducing such transitions and so the results are not necessarily conclusive for television viewing, but they do describe what the eye requires of a real colour transition.

Transitions between colour patches having luminances equal to each other (saturated red/green, magenta/blue, blue/green) require about 50% of the luminance bandwidth for undistorted observation. Transitions between saturated colours and white or grey depend on the colour; at equal luminance, the worst case found, orange/white, needs 70% while others (magenta/white, blue/grey, green/white) still need approximately 50%. If the colours are not of equal luminance, the required chrominance bandwidth reduces. For example at a luminance contrast ratio of 4:1 only 30% is required for any transition.

Colour transitions involving orange require the greatest bandwidth; this is perhaps not surprising since it is 'minus blue' and blue cannot be resolved well as discussed above. Colour transitions seen through lower bandwidths than those prescribed appear blurred. It should also be noted that these bandwidths apply to vertical and diagonal as well as horizontal transitions.

2.3 The equations of a linear colour transmission system

For completeness this is described here in some detail. The subject is also covered in more depth in Refs. 9, 10 and 11.

Any colour can be described by a set of tristimulus values, or by a luminance signal and two chromaticity coordinates which are related to those tristimulus values. For convenience, in this section the CIE 1931 system is used where the tristimulus values are the amounts of each of the CIE X Y and Z primaries which are needed to produce a visual match to the colour; the Y value is the luminance of the colour. Chromaticity coordinates can be derived by normalisation:

$$x = \frac{X}{X+Y+Z}, \quad y = \frac{Y}{X+Y+Z} \qquad (2.4)$$

and these describe the colour independently of the luminance.

For any colour, the output of a theoretical camera forms a set of tristimulus values in a colour space defined by the transmission primaries R G and B. These values are related to and can be derived from the CIE XYZ values via a linear matrix:

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} \mathrm{a}_{00} & \mathrm{a}_{01} & \mathrm{a}_{02} \\ \mathrm{a}_{10} & \mathrm{a}_{11} & \mathrm{a}_{12} \\ \mathrm{a}_{20} & \mathrm{a}_{21} & \mathrm{a}_{22} \end{bmatrix} \cdot \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \tag{2.5}$$

where a_{00}, a_{01}, a_{02} are the XYZ tristimulus values of the red primary, a_{10}, a_{11}, a_{12} are those of the green primary and a_{20}, a_{21}, a_{22} are those of the blue primary. The tristimulus values are linearly related to the chromaticity coordinates of the transmission primaries and produce the white point of the system when $R = G = B = 1$.

This equation is a statement of one of Grassman's laws[12], that any colour (here R G and B separately) can be matched by a linear combination of any three other colours (here X Y and Z) provided that none of them can be made by linearly combining the other two. It is a mathematical description of the classical school physics experiment of mixing light from three projectors to make a fourth colour. Note that the equality sign denotes visual colour matching and not a mathematical identity, and applies only to observers with normal colour vision. Defects of colour vision are beyond the scope of this Report.

In the interests of compatibility with monochrome displays, colour transmissions take the form of a luminance signal accompanied by separate colouring information coded in some way. In order to conserve bandwidth, the property of the eye to see less detail in colour than luminance is exploited by bandwidth limiting the colour-difference signals. They are also scaled such that they fill the available amplitude characteristic of the transmission system. Thus:

$$E_V = \mathrm{m}\,(E_R - E_Y), \quad E_U = \mathrm{n}\,(E_B - E_Y)$$

$$\text{and} \quad E_Y = \mathrm{b}_{10}\,E_R + \mathrm{b}_{11}\,E_G + \mathrm{b}_{12}\,E_B \tag{2.6}$$

where the b values are those used in Eq. 2.9 below. These colour-difference signals are deliberately made bipolar since they are usually transmitted on a subcarrier within the luminance spectrum; unipolar signals (e.g. R and B) could be used but they would reduce to zero only for pure green transmission. In the NTSC system, the chrominance signals are further modified and transmitted at different bandwidths from each other to exploit even further the properties of the eye described above. In the receiver, the RGB signals can be recovered:

$$E_R = \frac{E_U}{\mathrm{m}} + E_Y, \quad E_B = \frac{E_V}{\mathrm{n}} + E_Y$$

$$\text{and} \quad E_G = \frac{(E_Y - \mathrm{b}_{10}\,E_R - \mathrm{b}_{12}\,E_B)}{\mathrm{b}_{11}} \tag{2.7}$$

but only at low frequencies where the colour-difference signals are unaffected. At high frequencies where the colour-difference signals are reduced to zero:

$$E_R = E_Y, \quad E_B = E_Y, \quad E_G = E_Y \tag{2.8}$$

which is the balance condition for display of the system white point. Thus the original signals from the scene can be recovered in the receiver, with only high frequency coloured information missing.

At the display, the light produced can be expressed in XYZ values derived from the RGB values via the inverse matrix equation:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} \mathrm{b}_{00} & \mathrm{b}_{01} & \mathrm{b}_{02} \\ \mathrm{b}_{10} & \mathrm{b}_{11} & \mathrm{b}_{12} \\ \mathrm{b}_{20} & \mathrm{b}_{21} & \mathrm{b}_{22} \end{bmatrix} \cdot \begin{bmatrix} R \\ G \\ B \end{bmatrix} \tag{2.9}$$

The b values in this matrix are the tristimulus values of the XYZ primaries in terms of RGB; note that the matrix in Eq. 2.9 is the inverse of that in Eq. 2.5. From the XYZ tristimulus values, the chromaticity coordinates of the displayed colour can be derived, and the accuracy of the transmission system can be assessed by comparison of the source and display values.

2.4 Derivation of the matrices

Clearly, matrix coefficients are required in order to understand the operation of the system, and in order to code and decode the signals efficiently. The process of derivation of the matrices depends on the chromaticity coordinates of the transmission primaries, which are traditionally the same as the display primaries. The mathematical process is as follows:

a) Define the transmission primaries and the white point at which $R = G = B = 1$ (for PAL, SECAM and MAC the white point is at illuminant D65, corresponding to a daylight illuminant with a correlated colour temperature of 6503.6K):

	x	y
Red	x_r	y_r
Green	x_g	y_g
Blue	x_b	y_b
White	x_w	y_w

b) Invoke the display equation Eq. 2.9, using the white point tristimulus values obtained by setting $Y_w = 1$ and de-normalising the chromaticity coordinates, thus $X_w = x_w/y_w$ and $Z_w = z_w/y_w$, and $R = G = B = 1$. So:

$$\begin{bmatrix} X_w \\ Y_w \\ Z_w \end{bmatrix} = \begin{bmatrix} x_r & x_g & x_b \\ y_r & y_g & y_b \\ z_r & z_g & z_b \end{bmatrix} \cdot \begin{bmatrix} A_r \\ A_g \\ A_b \end{bmatrix} = \begin{bmatrix} \\ M \\ \\ \end{bmatrix} \cdot \begin{bmatrix} A_r \\ A_g \\ A_b \end{bmatrix} \tag{2.10}$$

where $z = 1 - x - y$ and the A values (unknown) represent the amounts of each of the *RGB* primaries needed to produce a match to the white point. This matrix can be inverted by conventional means to give the analysis as in Eq. 2.5:

$$\begin{bmatrix} A_r \\ A_g \\ A_b \end{bmatrix} = \begin{bmatrix} \\ M \\ \\ \end{bmatrix}^{-1} \cdot \begin{bmatrix} X_w \\ Y_w \\ Z_w \end{bmatrix} \tag{2.11}$$

and can then be solved to give the gains A. Multiplication of the chromaticity coordinates of each primary by its appropriate A value gives values for the display matrix (Eq. 2.9), and the inverse of that matrix gives values for the analysis matrix (Eq. 2.5).

c) It is possible to calculate the ideal camera taking characteristics for the chosen display primaries. Using the matrix values calculated above, the tabulated values of the CIE colour matching functions ($\bar{x}$, $\bar{y}$ and $\bar{z}$, — see Fig. 1) are passed through the analysis matrix (Eq. 2.5). These represent the (normalised) amounts of the primaries X, Y and Z needed to match each monochromatic wavelength in turn and are derived by measurement of human colour vision. The characteristics are the colour matching functions of the display primaries and will usually have negative lobes since some of the matrix coefficients are negative; this implies that the camera must deliver a negative response to light at some wavelengths. This is conventionally effected by interposing an electrical linear matrix between the camera RGB sensors and the processor; the result is less than perfect but is usually adequate.

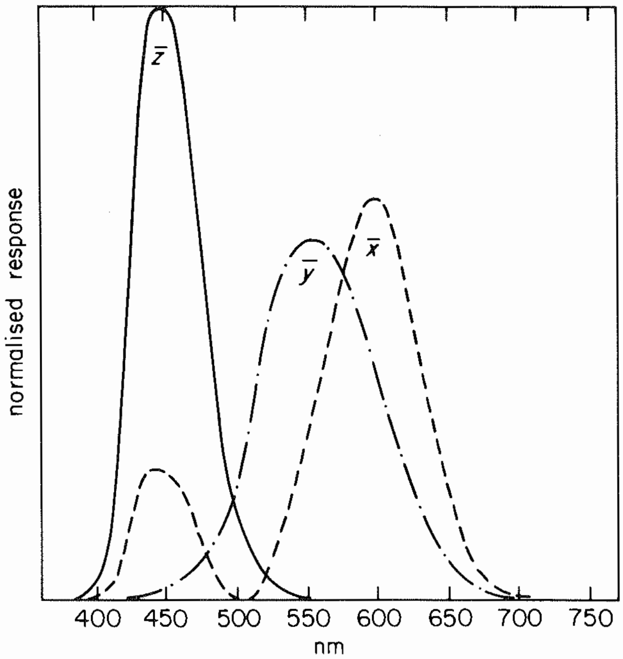


Fig. 1 - Colour matching functions of the CIE 1931 XYZ primaries, $\bar{x}\ \bar{y}\ \bar{z}$.

3. DESIRABLE FEATURES OF AN IMPROVED HDTV SYSTEM

Before proceeding further with the development of an improved colour coding system for use with HDTV, it is necessary to define in which ways such a new system needs to be better than that used for standard PAL, SECAM and MAC.

Firstly, it should obey the constant-luminance principle; the perceived luminance at the display should be directly related to the luminance of the source scene and not affected by any colour coding. Any coding system in which luminance is undistorted and colouring information carried with about 50% of luminance bandwidth could be described as a constant-luminance system. There have been many proposals for systems of this type [e.g. [2,3,13]]; these generally acknowledged that a true constant-luminance system was impractical at the time and concentrated on ways of modifying existing systems to approach constant-luminance performance.

Secondly, it should have a larger gamut of reproducible colours; this implies that new primaries must be selected.

Thirdly, in the case of transmission via HD-MAC channels, the received signals must be decodable by a standard MAC receiver and give acceptable colorimetric performance while retaining as many of the advantages of constant-luminance coding as possible.

In order to clarify how to achieve these aims, it is of interest to examine the MAC system to see in which ways it could be improved.

3.1 MAC system parameters

For the MAC system, the chromaticities of the primaries and white point are specified as:

	x	y	z
Red	0.64	0.33	0.03
Green	0.29	0.60	0.11
Blue	0.15	0.06	0.79
White	0.3127	0.3290	0.3583

Performing the calculations described in Section 2 gives:

$$\begin{bmatrix} A_r \\ A_g \\ A_b \end{bmatrix} = \begin{bmatrix} 0.67277 \\ 1.17776 \\ 1.18884 \end{bmatrix} \tag{3.1}$$

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 0.4306 & 0.3416 & 0.1783 \\ 0.2220 & 0.7067 & 0.0713 \\ 0.0202 & 0.1296 & 0.9392 \end{bmatrix} \cdot \begin{bmatrix} R \\ G \\ B \end{bmatrix} \tag{3.2}$$

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} 3.0632 & -1.3933 & -0.4758 \\ -0.9692 & 1.8760 & 0.0416 \\ 0.0679 & -0.2288 & 1.0693 \end{bmatrix} \cdot \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \tag{3.3}$$

Passing the colour matching functions ($\bar{x}$, $\bar{y}$ and $\bar{z}$, Fig. 1) through Eq. 3.3 produces the ideal camera taking characteristics shown in Fig. 2.

The transmitted signals are defined as:

$$\begin{aligned} E'_Y &= 0.299\ E'_R + 0.587\ E'_G + 0.114\ E'_B \\ E'_U &= 0.733\ (E'_B - E'_Y) \\ E'_V &= 0.927\ (E'_R - E'_Y) \end{aligned} \tag{3.4}$$

where the prime indicates the application of a transfer function (gamma) approximating to 0.45. The colour-difference gains are chosen so that a reasonable gamut of colours is carried by the system before limiting at ±0.5 volt. The bandwidths of the luminance and colour-difference signals are 5.5 MHz and approximately 1.5 MHz respectively.

The gamma law is applied to correct for the transfer function of the typical cathode ray tube display which approximates to a power law of between 2.4 and 2.8. The higher value is common in older displays which are grid driven[14], the lower value is more typical of modern displays which are cathode driven. The overall transfer function of the system is greater than unity, giving the pictures a slightly larger-than-life appearance which is more pleasing than an overall linear system.

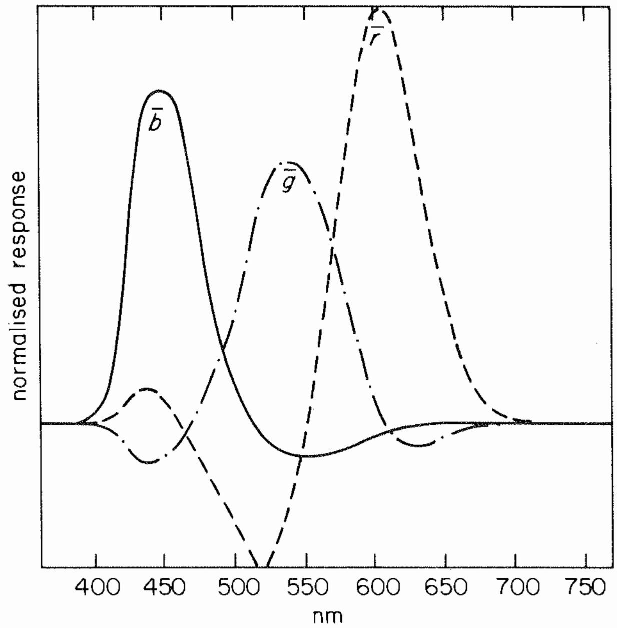


Fig. 2 - Colour matching functions of the MAC (EBU) RGB primaries, $\bar{r}\ \bar{g}\ \bar{b}$.

3.2 Comments on the MAC system

MAC deviates from the ideal linear system described in Section 2 in two ways. Firstly, the transmitted luminance signal E'_Y is derived from non-linear primary signals. Secondly, the proportions of R G and B used to formulate the luminance signal are incorrect for the transmission primaries. The multiplier proportions in the 'luminance' equation are actually taken from the display matrix appropriate for NTSC transmission primaries; thus this signal is not truly representative of the luminance — in general it is too small. In spite of this, the receiver can recover the green signal without recourse to electrical non-linearities:

$$E'_G = \frac{(E'_Y - 0.299\ E'_R - 0.114\ E'_B)}{0.587} \tag{3.5}$$

In this way, the $R'\,G'\,B'$ signals can be completely recovered and there is no distortion of colour or luminance except for errors due to mismatch between the display and transmission non-linearities. Clearly, since the 'luminance' signal was incorrectly formed but the $R'\,G'\,B'$ signals were correctly recovered, there must have been some transmission of luminance information in the colour-difference signals. In large areas of colour this is fully recovered, but in areas of coloured detail all the high-frequency luminance information transmitted in the colour-difference channels will be lost since the colour-difference signals are both band limited to about 1.5 MHz (less than 30% of luminance).

For example, if one attempts to transmit 100% colour bars the signals of Table 1 will appear throughout the system (for simplicity the transmission characteristics were taken to be 0.45 and 1/0.45, resulting in an overall linear system):

Table 1
MAC channel signals for 100% colour bars.

	Large area			Small area		
Colour	Red	Green	Blue	Red	Green	Blue
R_in	1.000	0.000	0.000	1.000	0.000	0.000
G_in	0.000	1.000	0.000	0.000	1.000	0.000
B_in	0.000	0.000	1.000	0.000	0.000	1.000
E'_Y	0.299	0.587	0.114	0.299	0.587	0.114
E'_U	−0.219	−0.430	0.650	0.000	0.000	0.000
E'_V	0.650	−0.544	−0.106	0.000	0.000	0.000
R_out	1.000	0.000	0.000	0.068	0.306	0.008
G_out	0.000	1.000	0.000	0.068	0.306	0.008
B_out	0.000	0.000	1.000	0.068	0.306	0.008
Y	0.222	0.707	0.114	0.068	0.306	0.008
x	0.640	0.290	0.150	0.313	0.313	0.313
y	0.330	0.600	0.060	0.329	0.329	0.329

Clearly, for large coloured areas the output equals the input.

However, at high frequencies only 30.8% of the luminance of red travels via the 'luminance' channel so 69.2% of luminance must have travelled in the colour-difference channels. Similarly for transmission of the green and blue primaries, 49.6% and 88.7% of luminance travels in colour-difference channels respectively. At complementary colour transitions which involve large changes in E'_U or E'_V, where the higher luminance frequencies in the colour-difference signals are lost due to filtering, the chromaticity coordinates of the output pass through those of white, and the true luminance value is that of the relevant matrix coefficient in Eq. 3.2.

In any colour transition, and in coloured areas, high frequency luminance components are severely attenuated. This effect is known as the 'failure of constant luminance' and is apparent on pictures as a dark banding between adjacent coloured areas and a softening of colour texture. To illustrate this effect, a green-to-magenta transition is analysed and shown in Fig. 3 as the received E'_Y E'_U E'_V signals, and in Fig. 4 as the displayed RGB signals (overall linearity assumed) together with the perceived luminance, Y. 'BBC' colour bars are used here where the values change between 25% and 100% in the non-linear signals; these are sometimes described as '95%' colour bars (actually this relates to the linear signal levels, 5% and 100%). For the purposes of these figures, the luminance bandwidth is taken to be precisely three times that of chrominance. Clearly, although the transmitted luminance is of high bandwidth, the perceived luminance changes at the speed of the chrominance change; also the luminance overshoots the final level, this is perceived as a dark band.

It is evident that the colour-difference signal gains, m and n, have been chosen such that a peak-to-peak signal range of 1.3 is required for the transmission of 100% colour bars. In the MAC system specification a peak-to-peak signal range of 1 is permitted, larger values being clipped to ±0.5; thus MAC cannot transmit its own primaries at full saturation.

A chromaticity diagram of the MAC primaries is shown in Fig. 5. This is a projection into two dimensions of a three-dimensional space, in which luminance is normal to the paper. The positions of the primaries are shown, together with the white point

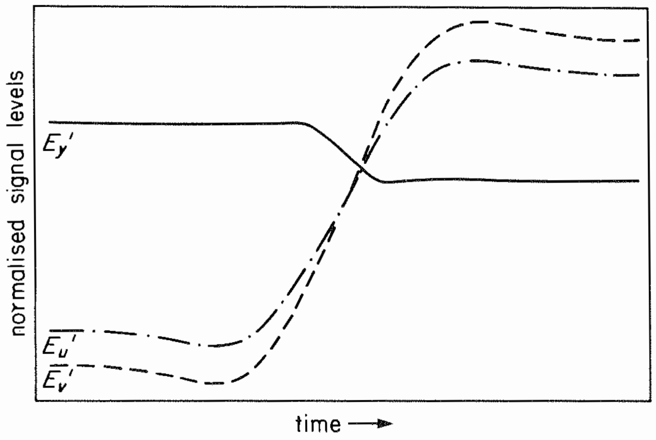


Fig. 3 - Received signal levels in a green-to-magenta transition in the standard MAC system.

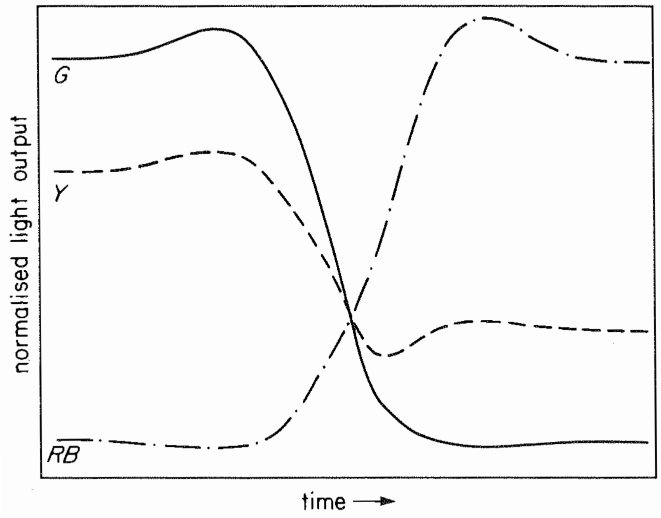


Fig. 4 - Displayed signal levels in a green-to-magenta transition of the standard MAC system.

(D65) and the outline of Pointer's Real Surface Colours gamut[15]. This represents the most saturated reflective colours measured in 1980, and is a reasonable estimate of the range of colours which a television system might have to reproduce. Clearly, since both red and green primaries fall within it, and the gamut excursces outside the triangle, values of R G and B are required which excurse both above unity and below zero in order to code the full gamut. Negative light output is not attainable in a display, and so those colours outside the triangle joining the primaries are not reproducible by the MAC system in any way.

3.2.1 Advantages of the MAC colorimetry system

The 'luminance' signal is non-linear in a way which closely mimics the non-linearity of the eye; thus any noise or other perturbations to it are rendered uniformly visible over the luminance range. The colour-difference signals are narrow band, less than 30% of luminance, and are numerically zero for an achromatic signal (non-coloured). They do not affect compatibility with a monochrome receiver which displays only the luminance signal. All processing in the receiver is done on non-linear signals by addition only, hence the signals at the studio can be coded and decoded without recourse to non-linearities.

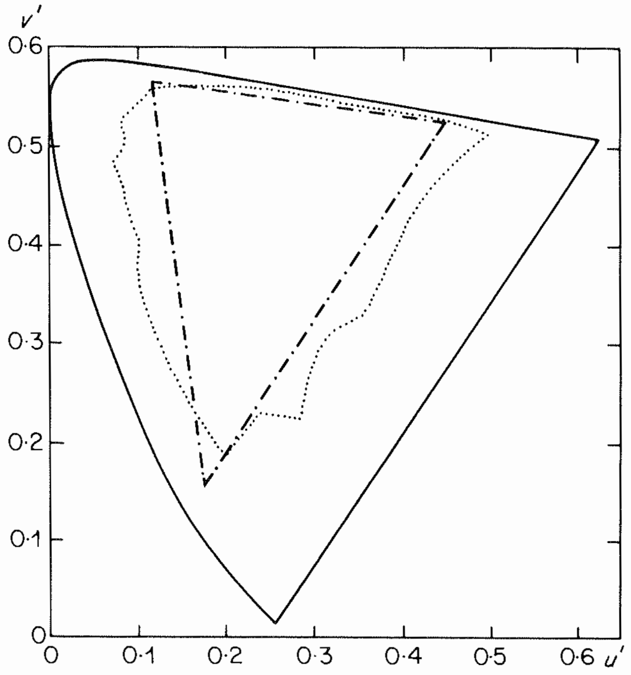


Fig. 5 - CIE 1976 chromaticity diagram showing the primaries of the standard MAC system, spectrum locus and boundary of Pointer's Real Surface Colours gamut.

——— Spectrum locus
—·—·— MAC system gamut
·········· Pointer's gamut

The displayed picture has, at colour transitions, a dark boundary line due to the luminance being too low during the transition. This helps to define the boundary and is akin to a child's drawing in which he outlines an area in black crayon and then fills it with colour, sometimes inaccurately. This effect is highly visible at the green/magenta transition in the standard colour bars test signal. It may seem strange to describe this as an advantage, but it is arguable that it helps to increase the apparent sharpness of displays which do not fully resolve the luminance signal, such as small cathode ray tubes with the precision-in-line (PIL) structure.

Such systems have been successfully used world wide since the beginning of colour television.

3.2.2 Disadvantages of the MAC colorimetry system

Detail in coloured areas is attenuated, and some is lost altogether due to the limited colour-difference channel bandwidths and conventional coding. This is not a great problem in a television system in which luminance and colouring signals share the same spectrum by using sub-carriers (PAL, SECAM), but when the confusions caused by the effects of sub-carriers are removed it is much more visible[16]. Also, the effect is greatly enhanced in large, high quality displays which fully resolve the luminance signal.

Matrix operations to transcode the *RGB* signals to suit other display primaries (such as are common in projectors) are imperfect if they are performed on the non-linear signals[17]. Such operations are becoming increasingly necessary as display device technology develops away from the conventional three gun shadow mask colour tube.

4. THE PROPOSED HDTV SYSTEM

4.1 System parameters

Constant-luminance coding was specified at the outset of the work described in this Report, and the primaries were chosen to encompass Pointer's Real Surface Colours gamut. The actual choice of primaries and transmission signal formulation were the subject of analysis aimed at producing a system whose transmitted signals could be decoded by a conventional MAC receiver and displayed without excessive colour errors. This acceptability is difficult to define and work was initially done entirely mathematically. Assessment of the compatible receiver display errors were made assuming a display with a transfer law of 1/0.45 and ideal EBU primaries. Fifteen test colours were used, those specified by the EBU for camera assessment[18], and errors were calculated as CIELUV δE^* values raised to the fourth power before summing.

Sixteen sets of primaries were examined for this compatibility study; these are listed in Appendix B. There was no formal optimisation process which could undertake the work objectively, so sets of three primaries were formed by inspection and the transmission parameters, including the system transfer law (gamma), were optimised for each set to produce a 'compatible' display. Of the sixteen sets examined Set 15 produced the best compatibility and the optimised transfer law most closely resembled the 0.45 value of the MAC system. It fully covers Pointer's Gamut and has some pleasing symmetries. The chromaticity coordinates of the primaries are:

	x	*y*	*z*
Red	0.6915	0.3083	0.0002
Green	0.0000	1.0000	0.0000
Blue	0.1440	0.0297	0.8263
White	0.3127	0.3290	0.3583

The white point is D65 as for MAC. The chromaticities of red and blue are those of spectral lines at 620 nm and 460 nm respectively. The line joining red and blue is parallel to the line of purples. The green is a non-real colour which lies outside the spectrum locus; although located at $x = 0$, $y = 1$ this does not imply that the green is a luminance signal, and so this is truly an *RGB* system and not an *RYB* system.

Performing the calculations described in Section 2 gives:

$$\begin{bmatrix} A_r \\ A_g \\ A_b \end{bmatrix} = \begin{bmatrix} 1.10010 \\ 0.62171 \\ 1.31756 \end{bmatrix} \tag{4.1}$$

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 0.7607 & 0.0000 & 0.1897 \\ 0.3392 & 0.6217 & 0.0391 \\ 0.0002 & 0.0000 & 1.0887 \end{bmatrix} \cdot \begin{bmatrix} R \\ G \\ B \end{bmatrix} \tag{4.2}$$

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} 1.3146 & 0.0000 & -0.2291 \\ -0.7171 & 1.6084 & 0.0672 \\ -0.0002 & 0.0000 & 0.9186 \end{bmatrix} \cdot \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \tag{4.3}$$

The transmission equations for best compatibility are:

$$\begin{aligned} E'_{Y\mathrm{h}} &= (0.3392\, E_{R\mathrm{h}} + 0.6217\, E_{G\mathrm{h}} + 0.0391\, E_{B\mathrm{h}})' \\ E'_{U\mathrm{h}} &= 0.7988\, (E'_{B\mathrm{h}} - E'_{Y\mathrm{h}}) \\ E'_{V\mathrm{h}} &= 1.8668\, (E'_{R\mathrm{h}} - E'_{Y\mathrm{h}}) \end{aligned} \tag{4.4}$$

where the suffix, h, is chosen to indicate values for an HDTV system. The prime indicates raising to the power 0.445; that this value is only 1% different from the MAC system value of 0.45 can be taken as a measure of the degree of compatibility achieved, particularly of the grey scale. The power law is taken as 0.45 in further discussion.

Passing the colour matching functions ($\bar{x}$, $\bar{y}$ and $\bar{z}$, Fig. 1) through Eq. 4.3 produces the ideal camera taking characteristics shown in Fig. 6. Note that the negative lobes are quite small.

By multiplying together the matrices of Eqs. 3.2 and 4.3, and Eqs. 3.3 and 4.2, it is possible to obtain

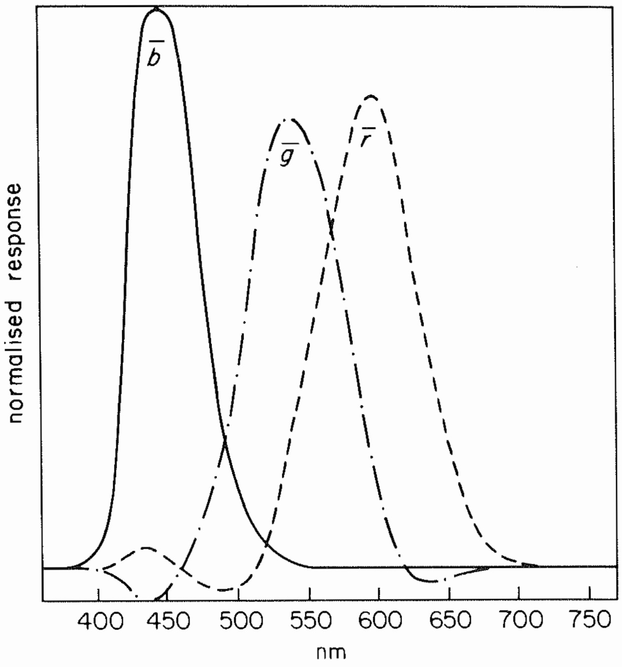


Fig. 6 - Colour matching functions of the proposed HDTV RGB primaries, $\bar{r}\ \bar{g}\ \bar{b}$.

conversion matrices relating MAC *RGB* tristimulus values (suffix m) to those in this HDTV system:

$$\begin{bmatrix} R_h \\ G_h \\ B_h \end{bmatrix} = \begin{bmatrix} 0.5614 & 0.4193 & 0.0193 \\ 0.0497 & 0.9004 & 0.0499 \\ 0.0184 & 0.1189 & 0.8627 \end{bmatrix} \cdot \begin{bmatrix} R_m \\ G_m \\ B_m \end{bmatrix} \tag{4.5}$$

$$\begin{bmatrix} R_m \\ G_m \\ B_m \end{bmatrix} = \begin{bmatrix} 1.8576 & -0.8662 & 0.0087 \\ -0.1011 & 1.1663 & -0.0652 \\ -0.0257 & -0.1423 & 1.1680 \end{bmatrix} \cdot \begin{bmatrix} R_h \\ G_h \\ B_h \end{bmatrix} \tag{4.6}$$

In the HDTV receiver, which correctly decodes the transmission, the linear *RGB* signals are recovered:

$$E_{R\mathrm{h}} = \left(\frac{E'_{V\mathrm{h}}}{0.7988} - E'_{Y\mathrm{h}}\right)'', \quad E_{B\mathrm{h}} = \left(\frac{E'_{U\mathrm{h}}}{1.8668} - E'_{Y\mathrm{h}}\right)''$$

$$E_{G\mathrm{h}} = \frac{(E'_{Y\mathrm{h}}{}'' - 0.3392\, E_{R\mathrm{h}} - 0.0391\, E_{B\mathrm{h}})}{0.6217} \tag{4.7}$$

where the double prime indicates raising to the power 1/0.45.

In order to compare the performances of the MAC and HDTV systems, it was assumed that the HDTV signal will be displayed on a conventional monitor, suited to the MAC system, with EBU primaries — indeed there is little hope of more saturated primaries until there is some major development in display technology. This implies that the wide-gamut advantages cannot be demonstrated at this stage, although pictures recorded with this gamut could be displayed accurately on any future device with a wider gamut than the MAC system. Hence, for the foreseeable future, the most accurate display method will be to convert the HDTV tristimulus values R_h G_h and B_h to tristimulus values in the MAC system using Eq. 4.6 (or the appropriate equation for the actual display primaries), and then raise the resultant values to the power 0.45 (or the reciprocal of the actual display transfer characteristic) for application to the display device. Such an operation makes extensive use of non-linear signal processing, however, and will add considerably to the cost of picture monitors and their potential for thermal drift. An alternative, although slightly less accurate, approach which may produce better results in practice is detailed in Section 5.

4.2 System performance

The colour gamut of the primaries totally encloses Pointer's Gamut of Real Surface Colours and thus can cope with the saturated yellows, cyans and magentas which lie outside the MAC primary gamut. Fig. 7 is a chromaticity diagram showing the location of the new primaries, with the MAC primaries shown for comparison together with the outer boundary of Pointer's Real Surface Colours gamut. The large extra area of greens covered by the new primaries are not highly significant, but are included as a result of the compatibility requirement. Fig. 8 shows the colour errors for the test colours used in the optimisation, when coded by the proposed system and decoded and displayed by the compatible MAC receiver. The full results are shown numerically in Table D1 in Appendix D. The mean error is 3.48 units of δE^*, the worst colour is number 9 (Medium Green) which has an error of 7.52 δE^* units.

The results are also shown in Photos 1 and 2. In general, the visual impact of the compatible system agreed well with the optimisation predictions. The test colours are shown as 15 patches, with black, grey and white added, together with the six colours of the 'BBC' or '95% bars' colour bars (100.0, 100.25). The colour bars are included to show the performance at more saturated colours, but were not taken into consideration during the system optimisation. The left hand side of each patch is the ideal reproduction of that colour, the right hand side has been processed via a constant-luminance coder and a standard decoder. In Photo 1, the constant-luminance coder used standard EBU/MAC primaries and the transmission parameters

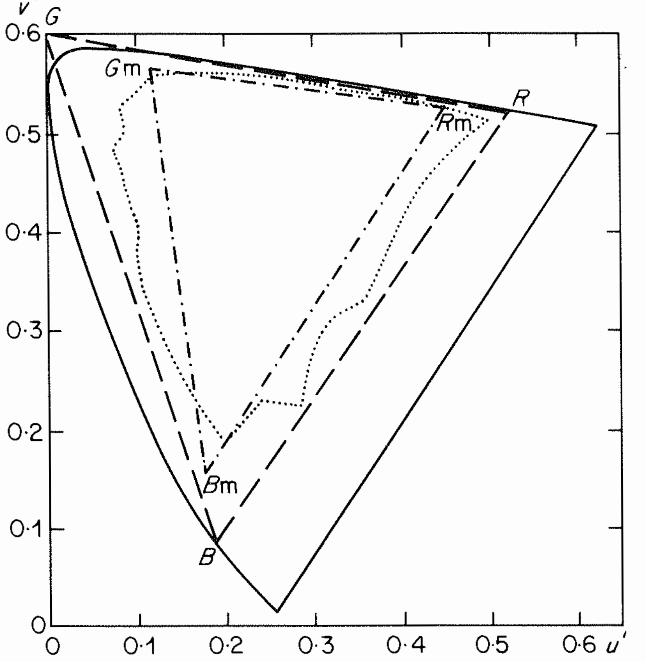


Fig. 7 - CIE 1976 chromaticity diagram showing the primaries of the proposed HDTV system, spectrum locus and boundary of Pointer's Real Surface Colours gamut.

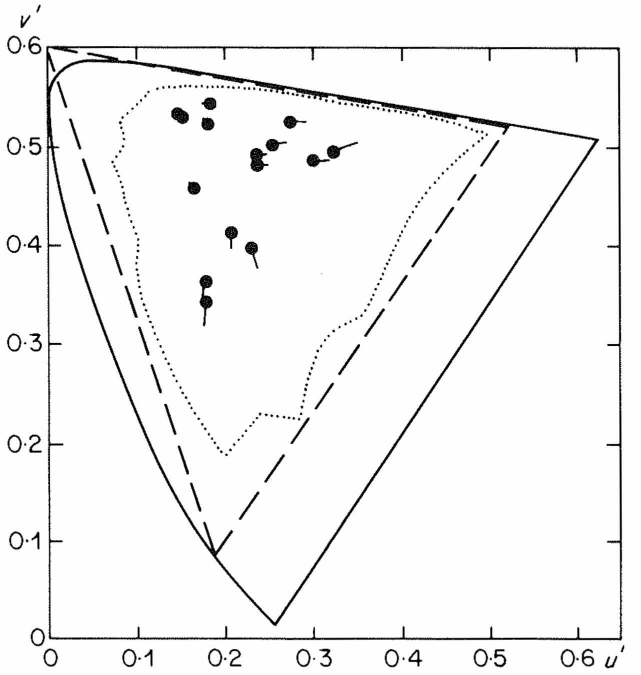


Fig. 8 - CIE 1976 chromaticity diagram showing the colour errors for a compatible MAC decoder operating with the proposed HDTV system.

derived as Set 1 in the Appendix. In Photo 2, the constant-luminance coder used Set 15, the proposed system. Clearly, the colour errors are much less for the Set 15 system, and are more evenly distributed.

4.2.1 Advantages of the new HDTV colour coding system

Since constant-luminance coding is specified, the decoder can perform a linear matrix operation to transform the *RGB* drive signals from those suited to the transmission primaries to match any particular set of display primaries without colour error for chromaticities inside the triangle formed by the display primaries themselves. Thus any new display technology which does not use conventional phosphors, such as lasers, liquid crystals etc, can be used without compromise.

Since all the perceived luminance travels exclusively via the luminance signal channel, there is no loss of luminance definition in coloured areas. This is a dramatic improvement for some pictures and is shown in the same green/magenta transition as was used to illustrate the luminance defects of the MAC system. Fig. 9 shows the received HD-MAC signals, Fig. 10 shows the decoded drive signals R_h G_h B_h, and Fig. 11 shows these values converted to R_m G_m B_m values for use on a MAC display by using Eq. 4.6. The failure of the red and blue signals to be co-sited results from rounding errors in the computing processes. This should be compared with the equivalent figures for the MAC system; clearly the perceived luminance change is much more rapid. It is interesting to note that the luminance transition sharpness is retained in the case of the compatible decoder, as shown in Fig. 12, although the colour rendition of such highly saturated colours is not particularly good.

Since non-linearities are required in the true HDTV decoder, it is easy to accommodate display transfer characteristics which differ from the standard cathode ray tube display.

To illustrate the colorimetric performance of the proposed system, a picture, 'Japanese Doll', has been digitally processed using a computer-based image processing system; the results are shown in Photo 3. Photo 3(a) shows the doll processed using the characteristics of a conventional MAC channel, and 3(b) shows processing using the characteristics of the new proposal, matrix converted for display on EBU primaries. Clearly the colorimetry is undistorted and there is a dramatic increase in sharpness of coloured detail. 3(c) shows the doll processed by the constant-luminance coder and a standard MAC decoder; the colours are somewhat distorted, reds becoming orange, but the sharpness advantage of constant-luminance coding is retained.

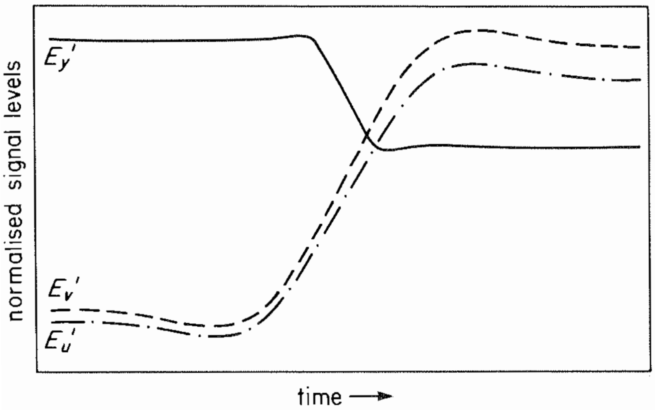


Fig. 9 - Signal levels in a green-to-magenta transition in the proposed HDTV system.

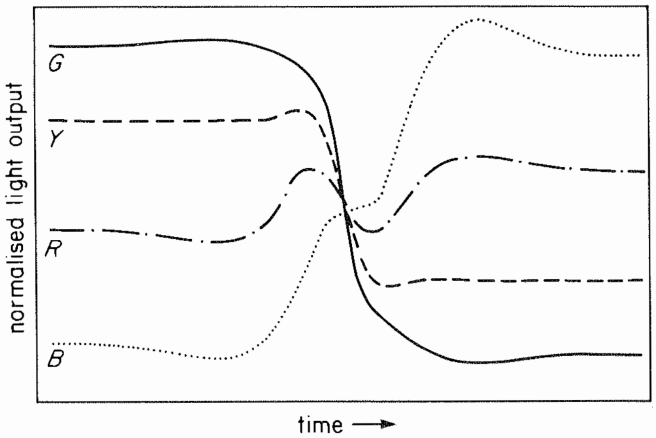


Fig. 10 - Displayed signal levels in a green-to-magenta transition of the proposed HDTV system.

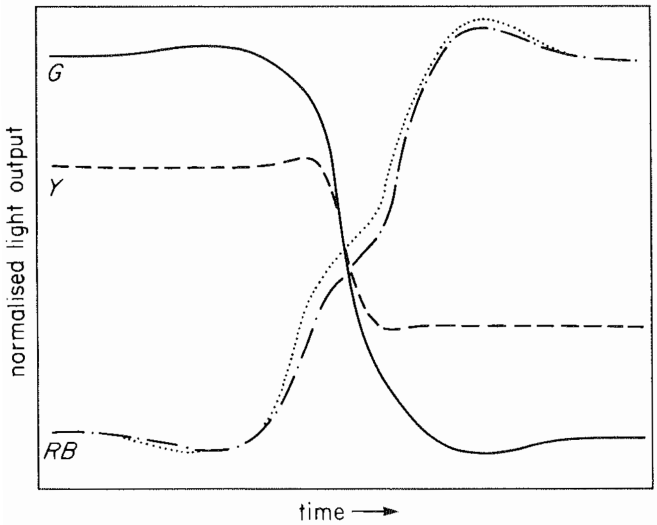


Fig. 11 - Displayed signal levels in a green-to-magenta transition of the proposed HDTV system, transformed to drive MAC primaries.

Comparison with the original picture (not shown here) indicates that if the colouring signals have about 50% of the horizontal and vertical resolutions of the luminance signal, there is practically no visible loss of colour definition at conventional viewing distances of three times picture height or more. The coded *YUV* signal thus retains the full quality of the *RGB* original, despite having only half of its bandwidth; this is a significant improvement on present-day practice.

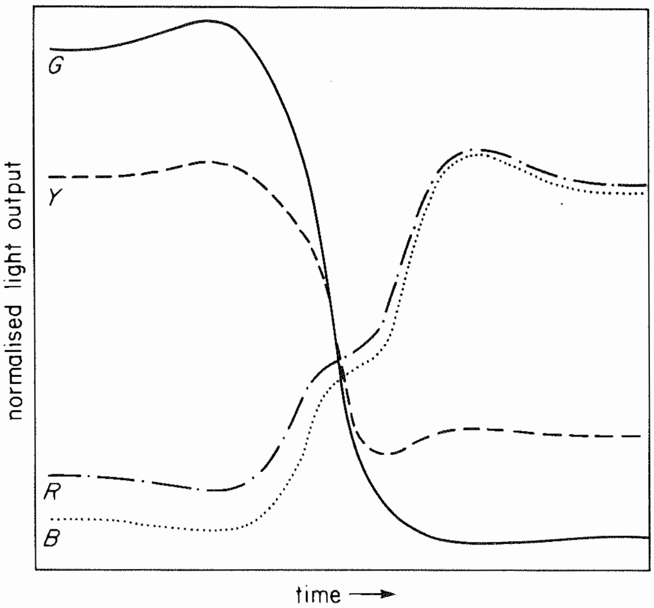


Fig. 12 - Displayed signal levels in a green-to-magenta transition of the proposed HDTV system, when decoded by a conventional decoder.

Noise is less apparent, since noise in the colour channels does not affect perceived luminance, but only the hue and saturation. Previous work[19] has shown that the eye is about 8 dB less sensitive to colour noise than luminance noise. As a corollary to this, the signal could travel through a noisier environment for the same subjective impairment. This important topic will be the subject of another Report in its own right[20].

4.2.2 Disadvantages of the new HDTV colour coding system

The receiver is more complex as it must contain non-linear circuits in order to recover the green signal. This may not be a problem in future digital receivers.

If the colouring channels do not have sufficient bandwidth, colour transitions will have a wrongly coloured boundary where luminance changes abruptly but the colouring changes more slowly. Experience so far indicates that, even with bandwidths of more than 30% of the luminance channel, some resolution loss may be visible in red and orange transitions. This is a small price to pay for the other advantages of the constant-luminance system and, in any case, has a considerably smaller visibility than the resolution losses incurred with conventional colour coding systems. It remains to be seen, however, whether practical problems will occur with chrominance bandwidths substantially less than 50% of the luminance value.

4.3 Implications for the transmission chain

4.3.1 Picture sources

There is little signal processing difference between standard coding and constant-luminance coding; Fig. 13 shows a conventional camera and Fig. 14 shows a constant-luminance camera. Note that the constant-luminance camera can be expected to be less prone to source noise since the colour-correcting linear matrix coefficients will generally be smaller, because of the smaller negative lobes in the desired responses. Also the colour-correcting matrix and the luminance coding matrix can be combined.

Other picture sources are similarly affected. Graphics devices will generate pictures directly in constant-luminance form, while telecines may require slightly modified forms of signal processing in order to correct for errors in the colours of the film dyes.

4.3.2 Receivers

Here there is a significant difference. Fig. 15 shows a conventional receiver and Fig. 16 shows a constant-luminance receiver. The inclusion of non-linearities presents a very significant problem in current generations of receiver. However future generations of HD-MAC receiver will make extensive use of digital signal processing in order to reassemble the HDTV picture; the non-linearities are relatively easy to accommodate by digital means, simply requiring a single PROM. Thus there should be very

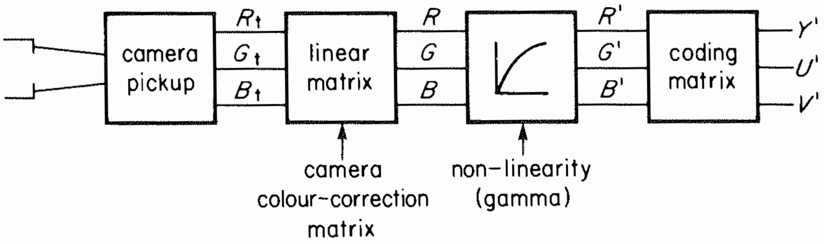


Fig. 13 - A studio camera operating on the standard MAC system (conventional).

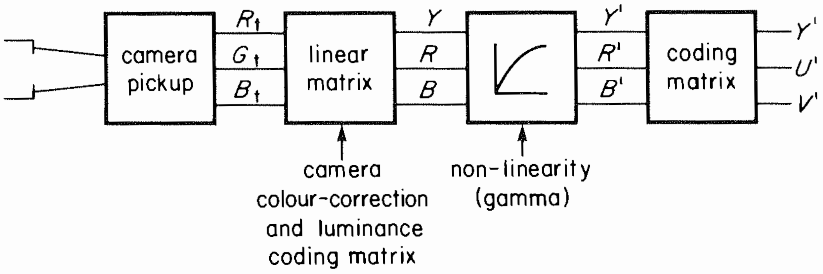


Fig. 14 - A camera operating on the proposed HDTV system.

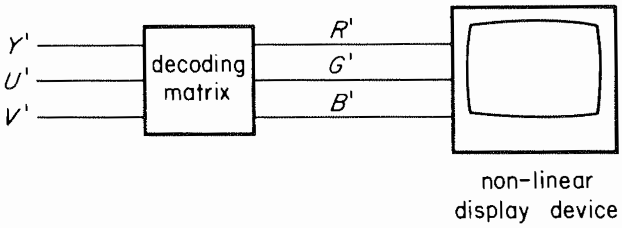


Fig. 15 - A receiver operating on the standard MAC system (conventional).

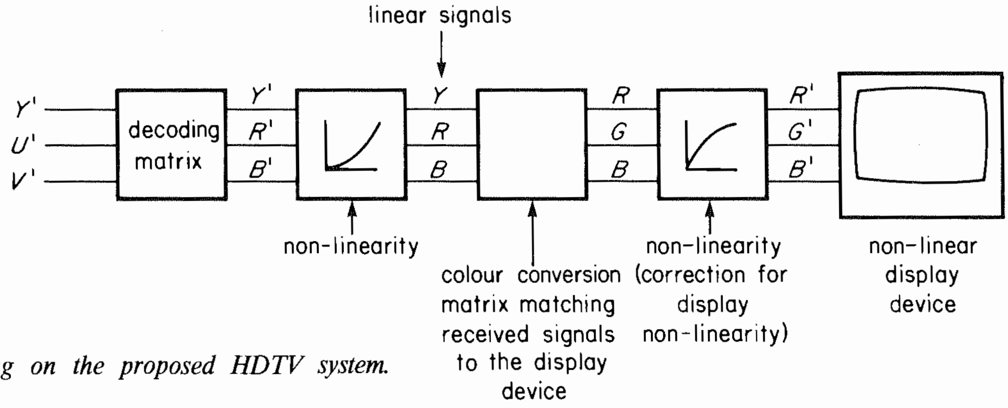

linear signals
Y'
U'
V'
decoding matrix
Y'
R'
B'
non-linearity
Y
R
B
R
G
B
R'
G'
B'
colour conversion matrix matching received signals to the display device
non-linearity (correction for display non-linearity)
non-linear display device

Fig. 16 - A receiver operating on the proposed HDTV system.

little barrier in future to the use of constant luminance posed by the receiver.

4.3.3 Signal processing

All conventional signal processing will function equally well on either type of signal. Recording will be unaffected. Any device which notionally decodes the signal for colour manipulation will inevitably need to be modified, but again this is only a mapping operation as described above for the receiver; the circuitry will be different but not necessarily more complex. Some attention must, however be paid to the number of quantisation levels required in digital equipment; the size of each interval will be much the same as at present (due partly to the compatible nature of the signal) but there may be a need for a greater number of quantising steps because of the greater colour gamut. This situation requires further investigation. It should, however, be pointed out that, if 9- or 10-bit digital coding is a problem in studio equipment, the range of the colour-difference signals may be limited (as in conventional MAC) without significantly affecting the majority of pictures.

4.3.4 Studio monitoring

In principle, the decoding required for studio picture monitors is very similar to that required in the receiver discussed in Section 4.3.2. However, in this instance the incoming signal will probably not be in digital form. There are therefore two possibilities for signal processing — to provide the necessary non-linearities in analogue circuitry, which may be subject to inaccuracy and drift, or to convert the signal into a digital representation for processing by similar circuitry to the receiver. This latter alternative is probably preferable, but rather complex.

Fortunately a third alternative exists, which may in practice prove preferable to either of the above approaches. In this alternative, exact decoding is not attempted; instead a piecewise-linear function is generated which approximates to the desired decoding characteristic. The correct linear segment of the function can be selected at any point using simple and drift-free analogue circuitry. This approach will be described fully in the following section.

5. MULTI-LINEAR MATRIX DISPLAYS

A conventional display, used to decode and present a constant-luminance coded signal aimed at wide gamut primaries, will produce acceptable colorimetry over a substantial portion of the colour gamut, as described above. The careful choice of primaries and optimisation of transmission parameters has reduced colorimetric errors to a level which is similar to the colour distortions produced in typical existing domestic receivers (which have a wide range of phosphor chromaticities) correctly decoding a MAC signal. However, for studio monitoring, greater fidelity is essential; advantage can be taken, however, of the acceptable colorimetry over a portion of the colour gamut. The piecewise-linear technique that results is known as 'Multi-linear Matrixing'[21]. It is not new, but does offer an acceptable compromise between accuracy and cost.

The multi-linear matrix aims to provide a variety of colour decoding matrices, each intended to produce good colorimetry over a restricted range of colours and luminances, using automatic selection of the appropriate matrix without recourse to logic switching. There is no analytical way of solving the mathematical problem; Percival[21] suggested making a physical model of the error space in plaster-of-Paris and taking measurements directly from it. With more computing power readily to hand it is now possible to use an iterative mathematical process to arrive at a variety of solutions. The results quoted below were derived from a spreadsheet by inspection of various formulations.

The set of 15 test colours used for the main system optimisation were not thought to be appropriate for this work since they do not fully explore the gamut of the MAC system. Fortunately, an established set of 26 colours was available which contains colours of higher saturation, these being those used by the BBC in colour television camera analysis[22]. Table D2 lists white and the test colours which were used to establish a numerical solution to this problem. Also listed are the colorimetric errors in reproduction by a theoretical standard MAC receiver decoding and displaying a constant-luminance coded HD-MAC signal. The errors are given in CIELUV values. The mean error is 4.98 δE^* units and the worst colour is number 3 (Saturated Cyan) which has an error of 15.84 δE^*.

Table D3 shows the signals after coding in the constant-luminance wide-gamut coder, the compatible display drive signals produced by a conventional decoder operating on this constant-luminance coded signal, and the required drive signals for accurate reproduction of each colour using the standard MAC primaries. Note that only gamma-corrected signals are available in the compatible decoder.

The solution adopted was to find, by inspection, formulae operating on the transmitted signals $E'_{Y\mathrm{h}}$ $E'_{U\mathrm{h}}$ $E'_{V\mathrm{h}}$ which, after clipping at zero, could be added to the decoded $E'_{R\mathrm{c}}$ $E'_{G\mathrm{c}}$ $E'_{B\mathrm{c}}$ signals, such that the resulting modified signals were closer to the desired values of E'_{Rm} E'_{Um} E'_{Bm}. The colorimetric significance of any error in these non-linear signals is deeply hidden, so in order to apply corrections only where they would do significant good, the results were continually analysed to show the colorimetric errors for the modified signals. The form of the electronics involved in such a practical solution is shown in Fig. 17, where the red signal is being modified by the output of a linear combination of E'_{Yh} E'_{Uh} E'_{Vh} which is rectified and thus operates only for a particular range of colours. In this way it is possible to perform corrections on particular colours, at specific ranges of luminance and saturation, while not affecting other colours at all.

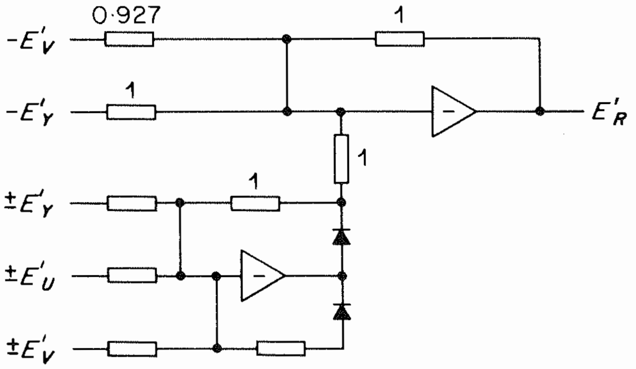


Fig. 17 - Multi-matrix colour correction of red drive signal.

A solution involving eight such correction signals was found and is shown in Fig. 18. The red signal is corrected mainly in saturated cyan and magenta, and the blue is corrected mainly in the yellow/orange region and in saturated magenta. Green is corrected in saturated blue and orange/red, and also in green and orange/yellow, pink/magenta regions. Skin tones, foliage and grey scale are completely unaffected. The results of these corrections on the displayed colours are shown in full in Table D4 in Appendix D. The mean error is reduced to 2.90 δE^* units, and the worst case colour is number 12 (Desaturated Green) which has an error of 7.39 δE^* units.

The errors listed in Table D4 should be compared with those in Table D2, for the unmodified MAC decoder. This is not a unique solution and it is probable that more efficient formulae and a more effective solution can be found. It is included merely to show that a method exists for the simple modification of a practical monitor, the signal modifiers could all be incorporated into a single device, taking the transmission signals (E'_Y E'_U E'_V) and connecting to the drive signals (R' G' B') via external adders.

To show the improvement effected by this means, the same green-to-magenta colour bar transition as was used for analysis earlier is shown in Fig. 19, coded by an HDTV coder and decoded by a conventional decoder incorporating the multi-linear matrix technique. Clearly, the perceived luminance change takes place at the same speed as the luminance signal, and the multi-linear matrix almost completely corrects the colour errors. Fig. 19 should be compared with Fig. 4 for the conventional MAC channel and Fig. 11 for the true HDTV channel.

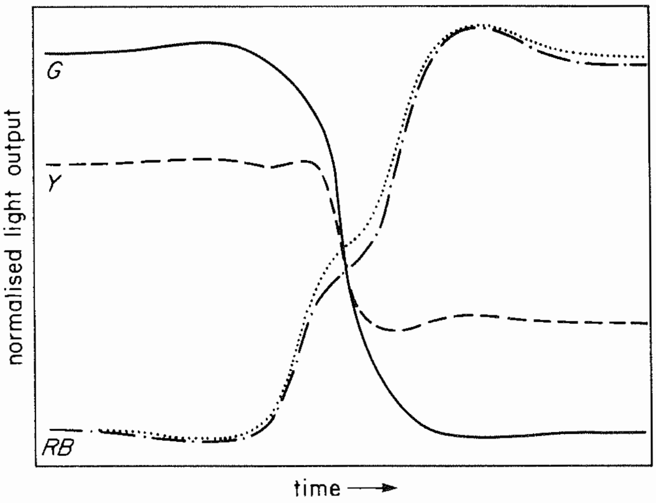


Fig. 19 - Displayed signal levels in a green-to-magenta transition of the proposed HDTV system in a compatible display, corrected by multi-linear matrixing.

The correction formulae are:

Red	(1)	$-E'_{Yh}/3$	$+\ E'_{Uh}/2$	$+\ E'_{Vh}/6$	when > 0
Red	(2)	$E'_{Yh}/8$	$+\ E'_{Uh}/6$	$+\ E'_{Vh}$	when < 0
Red	(3)	$E'_{Yh}/10$	$+\ E'_{Uh}/10$	$-\ E'_{Vh}/8$	when < 0
Green	(1)	$E'_{Yh}/4$	$+\ E'_{Uh}/8$	$-\ E'_{Vh}/2$	when < 0
Green	(2)		$E'_{Uh}/6$	$+\ E'_{Vh}/4$	when < 0
Green	(3)	$E'_{Yh}/6$	$-\ E'_{Uh}/2.5$	$-\ E'_{Vh}/3.5$	when < 0
Blue	(1)	$E'_{Yh}/4$	$+\ E'_{Uh}$	$+\ E'_{Vh}/5$	when < 0
Blue	(2)	$E'_{Yh}/7$	$+\ E'_{Uh}/7$	$-\ E'_{Vh}/7$	when < 0

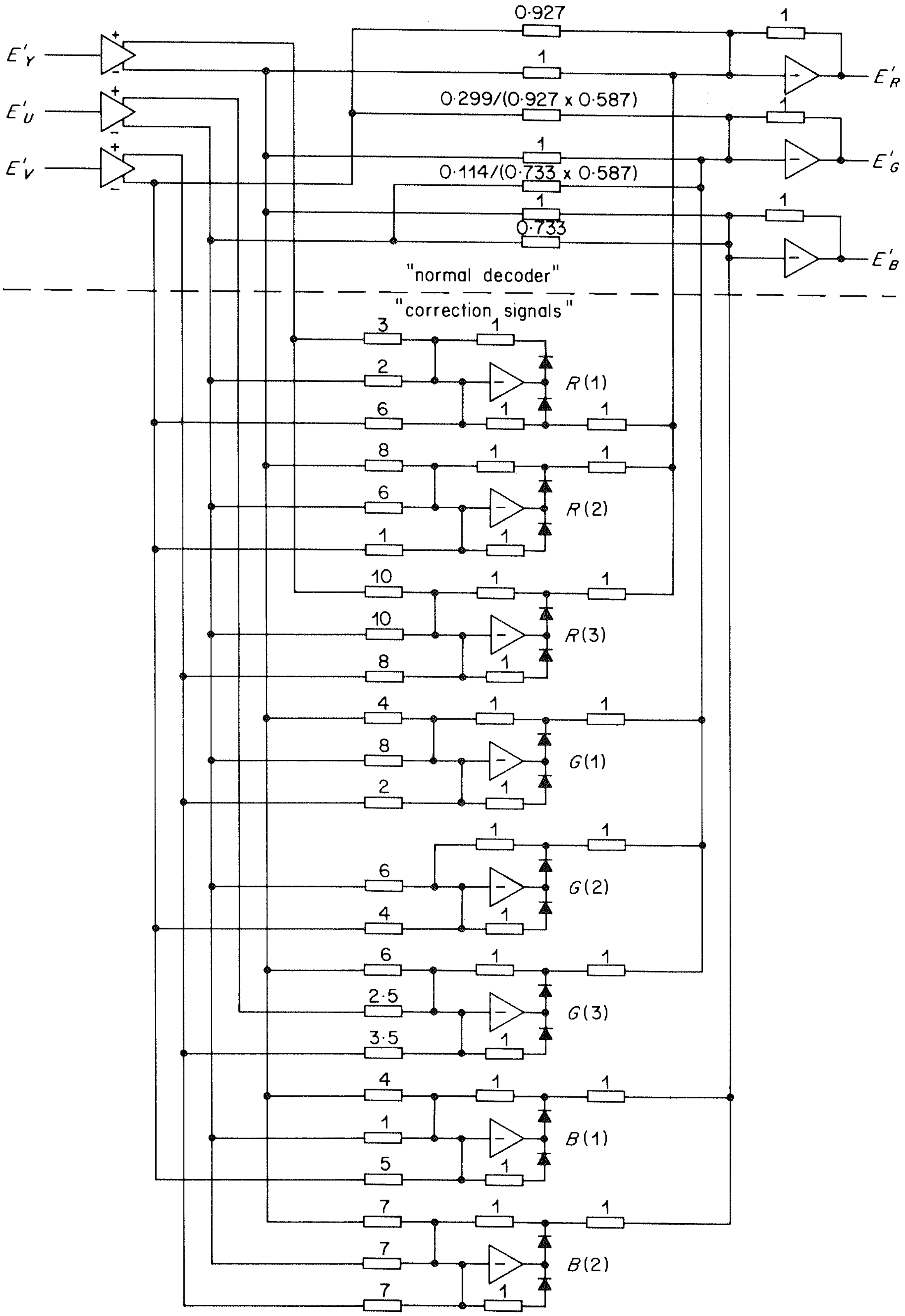
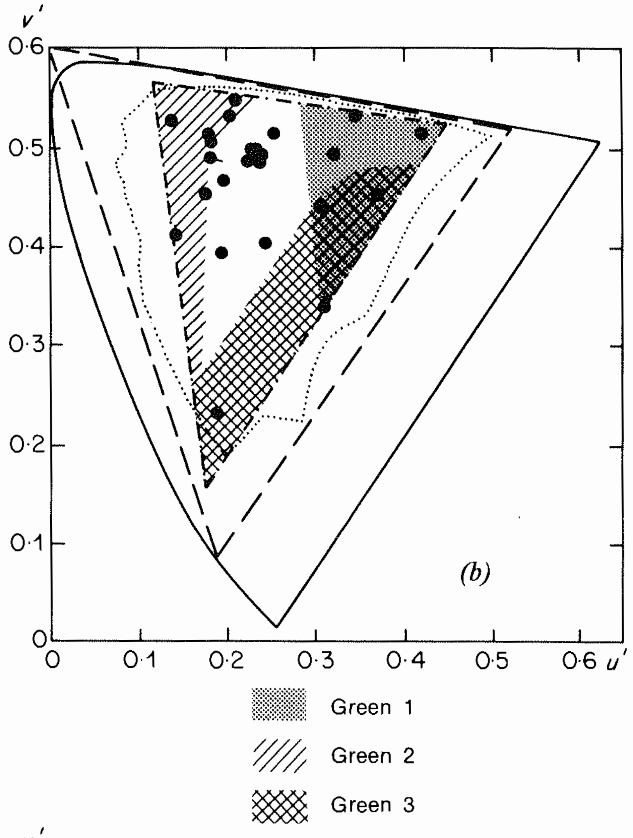


Fig. 18 - A monitor operating on the proposed HDTV system, using conventional decoding with multi-matrix colour correction.

Fig. 20 is three chromaticity diagrams showing the areas in which each of the eight correcting signals are active and the colorimetric errors remaining after multi-linear matrix correction.

The performance of the modified decoder/monitor is illustrated in Photos 4 to 6. Photo 4 shows the EBU test colours as patches in the same arrangement as for Photos 1 and 2, but this time with ideal reproduction (left), modified compatible (centre) and unmodified compatible (right). There is a significant improvement in colour fidelity, although these colours are not sufficiently saturated to show great improvements. Photo 5 shows the BBC test colours used to derive the modified decoder/monitor, and the improved fidelity is much more evident.

The Japanese Doll picture was reprocessed, using constant-luminance coding and decoding by a modified decoder. The result is shown in Photo 6; colour fidelity is markedly improved and the colour sharpness advantage is fully retained.



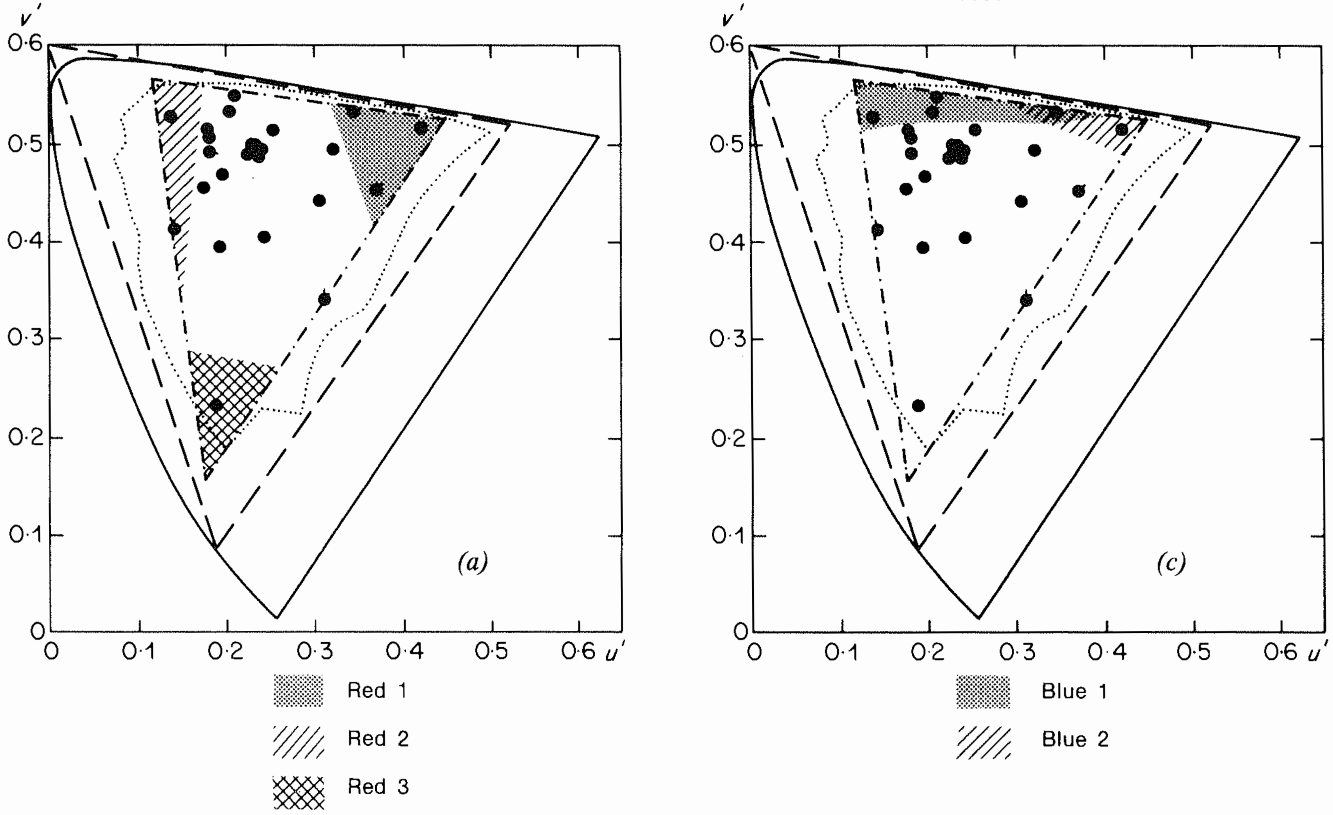


Fig. 20 - CIE 1976 chromaticity diagram showing the areas of correction by the multi-linear matrix and the remaining colorimetric errors.

——— Spectrum locus
— — Proposed HDTV gamut
—·—·— MAC system gamut
·········· Pointer's gamut
● Test colour error

(Note: the skin tone colours are not shown, for clarity).

6. CONCLUSIONS

It has been demonstrated that it is possible to design a television system which has an improved colour gamut and which obeys the constant-luminance principle in its coding, while retaining a considerable degree of compatibility with conventional decoders. The resulting pictures are sharper than for conventional coding, less prone to all sources of noise and permit linear transformation to suit any display primaries, thus making the system suitable for use at a time when display technology is advancing rapidly. The sharpness advantage is retained even when the signals are viewed on a conventional decoder, and noise performance is no worse than for conventional coding systems. Although the required decoder is necessarily more complex than a conventional system, advancing technology may render this irrelevant in the near future, and a simple additional circuit for conventional decoders to improve the degree of compatibility has been demonstrated.

Given that a chance to improve television colorimetry is a rare occurrence, it seems highly appropriate to grasp the opportunity at this time of development of a new High Definition Television system, at least within Europe if not the rest of the world. This system has been proposed to the Eureka Project 95 consortium for adoption within Europe as the standard for High Definition Television, and has provoked much argument and experimentation. It is hoped that the arguments are persuasive and that it, or a system with similar properties, will be adopted for use in any new television system to be defined for broadcast use.

7. ACKNOWLEDGEMENTS

The author wishes to thank I. Childs for his contributions to the theoretical aspects of this work, particularly the Multi-linear Matrix technique, E.W. Taylor for help with colour theory, N.J. Goodship for all the picture processing, and C.R. Nokes for his work on aspects of noise performance of the systems.

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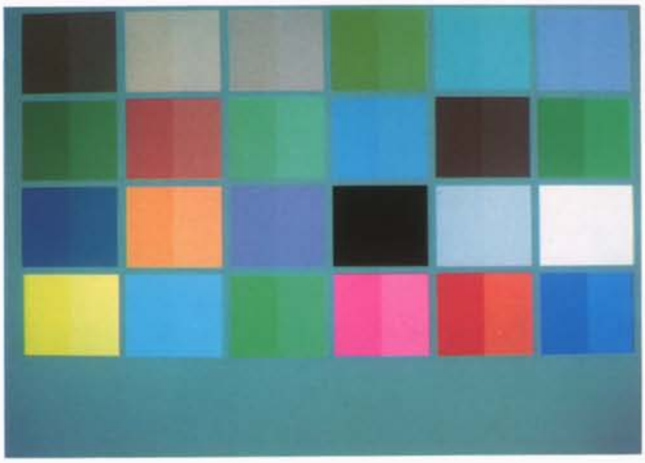


Photo 1
EBU test colour patches showing ideal reproduction (left) and compatible reproduction (right) using primaries Set 1.

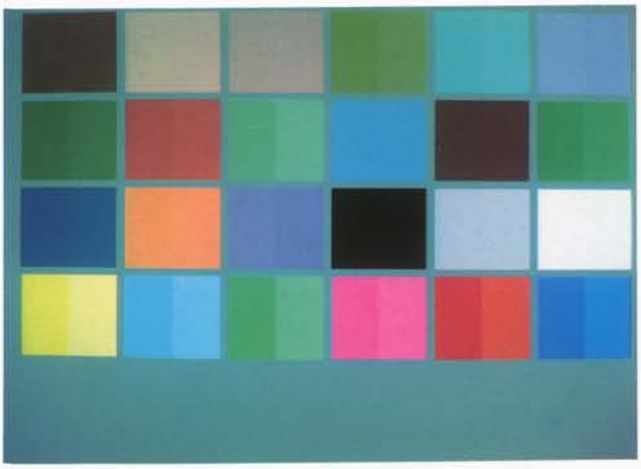
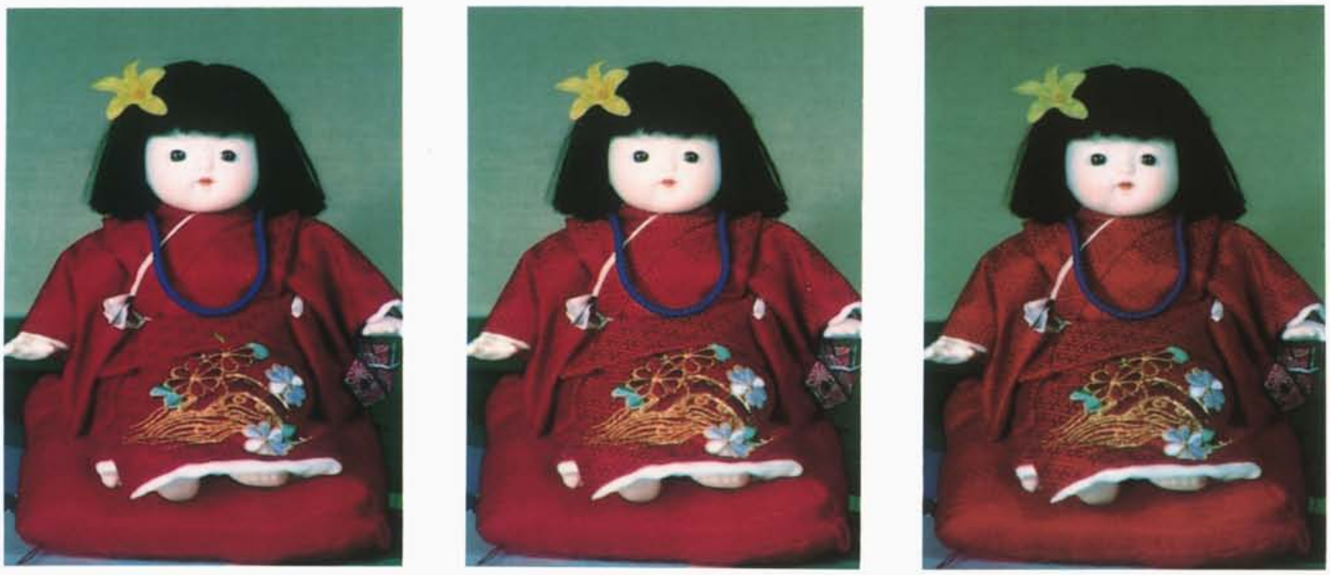


Photo 2
EBU test colour patches showing ideal reproduction (left) and compatible reproduction (right) using primaries Set 15.



(a) *(b)* *(c)*

Photo 3: Japanese Doll.
(a) Processed via standard MAC channel.
(b) Processed via constant-luminance channel with Set 15 primaries, matrix converted for display on EBU/MAC primaries.
(c) Processed via constant-luminance coder as for 3(b) and standard MAC decoder as for 3(a).

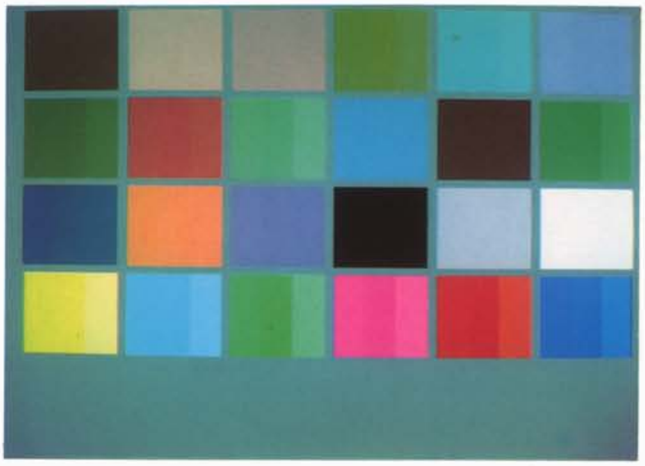


Photo 4
EBU test colour patches showing ideal reproduction (left), compatible reproduction (right), and modified compatible reproduction (centre).

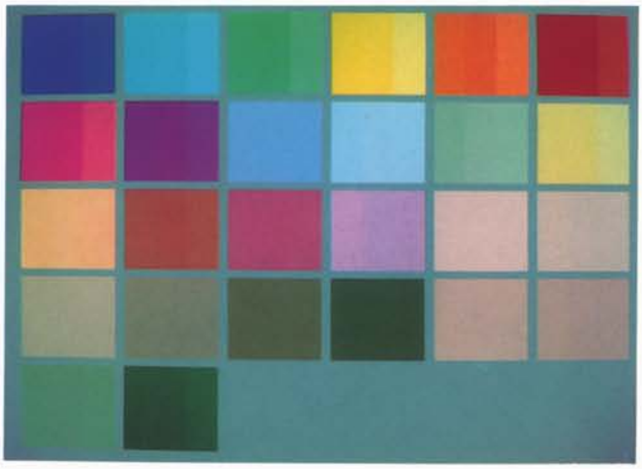


Photo 5
BBC test colour patches showing ideal reproduction (left), compatible reproduction (right), and modified compatible reproduction (centre).

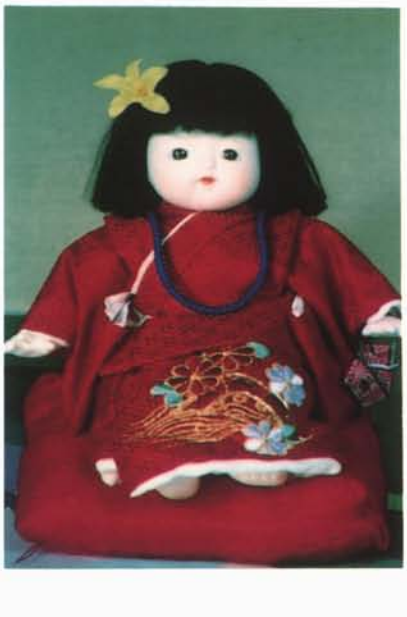


Photo 6: Japanese Doll processed via constant-luminance coder and modified MAC decoder.

APPENDIX A

Test Colours

The test colours used to evaluate the primary sets, shown in Appendix B, are the EBU set of fifteen colours, designed to test the analysis of cameras working on the standard EBU/MAC primaries, and shown in Table A1.

Table A1

Test colours used for system optimisation

		CIE 1976			CIELUV		
No.	Colour	Y	u'	v'	L^*	C^*	S^*
1	Dark Skin	0.0950	0.2539	0.5027	36.9	31.6	0.85
2	Light Skin	0.3710	0.2357	0.4931	67.4	39.6	0.59
3	Light Greyish Red	0.3000	0.2384	0.4837	61.7	34.8	0.56
4	Light Yellow Red	0.2960	0.1839	0.5453	61.3	62.3	1.02
5	Light Bluish Green	0.3010	0.1640	0.4581	61.7	28.4	0.46
6	Light Violet	0.3010	0.2067	0.4138	61.7	44.4	0.72
7	Foliage	0.1290	0.1804	0.5235	42.6	32.1	0.75
8	Medium Red	0.1900	0.3246	0.4960	50.7	85.5	1.69
9	Medium Green	0.4410	0.1520	0.5329	72.3	74.4	1.03
10	Medium Blue	0.1980	0.1770	0.3658	51.6	70.2	1.36
11	Dark Red	0.0650	0.3002	0.4882	30.6	41.5	1.36
12	Dark Green	0.2010	0.1471	0.5339	52.0	56.0	1.08
13	Dark Blue	0.0630	0.1786	0.3431	30.2	49.7	1.65
14	Medium Yellow Purple	0.4260	0.2757	0.5262	71.3	89.9	1.26
15	Medium Purple	0.1980	0.2307	0.3981	51.6	52.0	1.01

The second set of test colours used to evaluate the multi-linear matrix solutions are the BBC set of 26 colours, designed to test the analysis of cameras working on the standard EBU/MAC primaries, and shown in Table A2. White is also included as colour 1.

Table A2
Test colours used for multi-linear matrix optimisation

		CIE 1976			CIELUV		
No.	Colour	*Y*	*u'*	*v'*	*L**	*C**	*S**
1	White (D65)	1.0000	0.1978	0.4683	100.0	0.0	0.0
2	Saturated Blue	0.0466	0.1886	0.2352	25.7	78.1	3.0
3	Saturated Cyan	0.3314	0.1408	0.4139	64.3	65.8	1.0
4	Saturated Green	0.3310	0.1357	0.5298	64.2	73.0	1.1
5	Saturated Yellow	0.7240	0.2093	0.5510	88.2	95.7	1.1
6	Saturated Orange	0.3181	0.3462	0.5351	63.2	133.7	2.1
7	Saturated Red	0.1506	0.4212	0.5158	45.7	135.7	3.0
8	Saturated Pink	0.2373	0.3700	0.4530	55.8	125.4	2.2
9	Saturated Magenta	0.1283	0.3113	0.3414	42.5	94.1	2.2
10	Desaturated Blue	0.3000	0.1924	0.3969	61.7	57.4	0.9
11	Desaturated Cyan	0.5675	0.1756	0.4573	80.0	25.8	0.3
12	Desaturated Green	0.4491	0.1771	0.5169	72.8	50.0	0.7
13	Desaturated Yellow	0.5979	0.2051	0.5358	81.7	72.1	0.9
14	Desaturated Orange	0.4586	0.2541	0.5154	73.5	70.1	1.0
15	Desaturated Red	0.1712	0.3213	0.4961	48.4	79.7	1.6
16	Desaturated Pink	0.1769	0.3068	0.4439	49.1	71.3	1.5
17	Desaturated Magenta	0.3478	0.2427	0.4063	65.6	65.3	1.0
18	Skin Tone	0.4404	0.2221	0.4884	72.3	29.6	0.4
19	Skin Tone	0.3936	0.2246	0.4908	69.0	31.4	0.5
20	Skin Tone	0.3363	0.2280	0.4997	64.7	36.6	0.5
21	Skin Tone	0.2124	0.2320	0.5008	53.2	32.6	0.6
22	Skin Tone	0.1207	0.2397	0.4965	41.3	27.1	0.7
23	Skin Tone	0.0688	0.2223	0.4889	31.5	13.1	0.4
24	Skin Tone	0.3305	0.2330	0.4917	64.2	35.3	0.5
25	Skin Tone	0.2922	0.2376	0.4887	61.0	35.5	0.6
26	Light Foliage	0.2338	0.1813	0.5091	55.5	31.7	0.6
27	Dark Foliage	0.0656	0.1801	0.4927	30.8	12.1	0.4

APPENDIX B

Colour Primary Sets Evaluated For HDTV Use

Sixteen sets of primaries were defined. Sets 3 to 13 inclusive were the subject of similar investigation by CCETT in Rennes, France, as part of parallel work on the colorimetry of a proposed HDTV system. The sets are listed below, each together with a brief analysis of its performance as a compatible constant-luminance coded system. The optimisation process summed the CIELUV δE^* errors, each weighted by saturation S^* to avoid giving highly saturated colours undue importance. Errors were summed to the fourth power in optimisation. As a check on the validity of the optimisation, two sets of primaries were rechecked, using linear error summing, and excluding gamma. The results are not given here, but clearly indicated that linear summing allowed individual colour errors to be dominant, and exclusion of gamma from the optimisation always resulted in a poorer overall performance.

Table B contains a listing of the primary sets, the optimised transmission parameters, and a brief resumé of the colorimetric performance of the optimised system. Throughout this work, primary chromaticities have been used as the CIE 1931 x y values, they are also given here in CIE 1976 u' v' values rounded to three decimal places. Whenever a monochromatic primary is used, it is also given as a wavelength and this should be used as the specification of the primary in conjunction with the relevant CIE data tables[7].

Table B

Primary sets investigated for optimisation.

Set 1. EBU/MAC standard primaries.

	x	y	u'	v'
Red	0.640	0.330	0.451	0.523
Green	0.290	0.600	0.121	0.561
Blue	0.150	0.060	0.175	0.158

$$\text{Gamma} = 0.421$$
$$U' = 0.6536\,(B' - Y')$$
$$V' = 0.8680\,(R' - Y')$$

	δL^*	δC^*	δH^*	δE^*
Skin tones	0.26	0.17	7.47	7.74
Low saturation	0.62	−0.32	4.40	5.58
Medium saturation	4.13	4.69	2.10	7.42
High saturation	0.19	−4.37	2.42	6.06
All colours	1.37	−0.27	3.54	6.52

Table B: Primary sets investigated for optimisation (cont.).

Set 2. G4/col spectral primaries.

These were initially proposed by EBU Specialist Group G4/col for consideration for HDTV, before the requirement for compatibility with MAC receivers was established. They were derived from the wavelengths of light from available lasers.

	x	y	u'	v'	nm
Red	0.708	0.292	0.557	0.517	630.1
Green	0.131	0.819	0.042	0.587	529.0
Blue	0.129	0.049	0.155	0.132	468.1

$$\text{Gamma} = 0.440$$
$$U' = 0.7501\,(B' - Y')$$
$$V' = 1.6078\,(R' - Y')$$

	δL^*	δC^*	δH^*	δE^*
Skin tones	−0.40	−0.06	4.38	4.60
Low saturation	0.37	−0.56	3.08	4.48
Medium saturation	3.65	2.45	2.57	6.13
High saturation	0.31	−1.66	2.00	4.02
All colours	1.12	−0.62	2.76	4.78

Set 3. EBU/MAC primaries, monochromatic dominant wavelengths.

	x	y	u'	v'	nm
Red	0.672	0.328	0.481	0.528	611.3
Green	0.273	0.718	0.099	0.583	547.0
Blue	0.137	0.037	0.173	0.105	464.3

$$\text{Gamma} = 0.433$$
$$U' = 0.7678\,(B' - Y')$$
$$V' = 1.0802\,(R' - Y')$$

	δL^*	δC^*	δH^*	δE^*
Skin tones	−0.43	−0.23	5.52	5.72
Low saturation	0.41	−0.19	3.44	4.81
Medium saturation	3.87	2.90	2.70	6.74
High saturation	0.22	−3.15	1.96	4.54
All colours	1.16	−0.36	3.03	5.35

Table B: Primary sets investigated for optimisation (cont.).

Set 4. EBU blue dominant wavelength, spectral red and green chosen to form tangents to Pointer's Real Surface Colours gamut from blue.

	x	y	u'	v'	nm
Red	0.692	0.308	0.521	0.522	620.2
Green	0.090	0.833	0.028	0.585	522.0
Blue	0.137	0.037	0.173	0.105	464.3

$$\text{Gamma} = 0.441$$
$$U' = 0.7462\,(B' - Y')$$
$$V' = 1.6839\,(R' - Y')$$

	δL^*	δC^*	δH^*	δE^*
Skin tones	−0.39	0.08	4.26	4.45
Low saturation	0.37	−0.78	2.87	4.06
Medium saturation	3.45	1.64	2.33	5.18
High saturation	0.40	−1.70	1.38	3.35
All colours	1.10	−0.32	2.41	4.17

Set 5. Red and blue taken from Set 4 above, arbitrary non-real green.

Test to establish the effect of the green primary.

	x	y	u'	v'	nm
Red	0.692	0.308	0.521	0.522	620.2
Green	−0.074	0.988	−0.020	0.593	
Blue	0.137	0.037	0.173	0.105	464.3

$$\text{Gamma} = 0.445$$
$$U' = 0.7551\,(B' - Y')$$
$$V' = 2.0742\,(R' - Y')$$

	δL^*	δC^*	δH^*	δE^*
Skin tones	−0.38	0.06	3.59	3.75
Low saturation	0.39	−0.95	2.44	3.55
Medium saturation	3.30	0.88	2.30	4.78
High saturation	0.51	−1.21	0.90	3.10
All colours	1.10	−0.42	2.04	3.75

Table B: Primary sets investigated for optimisation (cont.).

Set 6. Red and green taken from Set 4 above, arbitrary non-real blue.

Test to establish the effect of the blue primary.

	x	y	u'	v'	nm
Red	0.692	0.308	0.521	0.522	620.2
Green	0.090	0.833	0.028	0.586	522.0
Blue	0.095	0.019	0.125	0.056	

$$\text{Gamma} = 0.439$$
$$U' = 0.7307\,(B' - Y')$$
$$V' = 1.8641\,(R' - Y')$$

	δL^*	δC^*	δH^*	δE^*
Skin tones	−0.42	−1.56	3.95	4.63
Low saturation	0.33	−0.48	4.64	6.37
Medium saturation	4.27	5.48	5.23	10.21
High saturation	0.06	−2.62	5.11	7.56
All colours	1.19	0.25	4.86	7.56

Set 7. G4/col spectral red, green taken from Set 4 above, arbitrary non-real blue.

Test to establish the effect of the blue primary.

	x	y	u'	v'	nm
Red	0.708	0.292	0.557	0.517	630.1
Green	0.090	0.833	0.028	0.585	522.0
Blue	0.096	0.035	0.119	0.098	

$$\text{Gamma} = 0.439$$
$$U' = 0.7289\,(B' - Y')$$
$$V' = 1.8641\,(R' - Y')$$

	δL^*	δC^*	δH^*	δE^*
Skin tones	−0.42	−1.49	3.95	4.60
Low saturation	0.33	−0.50	4.57	6.29
Medium saturation	4.24	5.35	5.14	10.06
High saturation	0.28	−2.58	5.00	7.44
All colours	1.26	0.24	4.79	7.45

Table B: Primary sets investigated for optimisation (cont.).

Set 8. G4/col spectral red and blue, non-real green chosen to form a tangent to the spectrum locus from red.

	x	y	u'	v'	nm
Red	0.708	0.292	0.557	0.517	630.1
Green	0.000	1.000	0.000	0.600	
Blue	0.129	0.049	0.155	0.132	468.1

$$\text{Gamma} = 0.443$$
$$U' = 0.7922\,(B' - Y')$$
$$V' = 1.9292\,(R' - Y')$$

	δL^*	δC^*	δH^*	δE^*
Skin tones	−0.38	−0.03	3.58	3.77
Low saturation	0.38	−0.70	2.49	3.85
Medium saturation	3.41	1.15	2.34	5.15
High saturation	0.42	−0.88	1.36	3.32
All colours	1.10	−0.17	2.22	4.01

Set 9. Red and blue taken from Set 3 above, non-real green taken from Set 8 above.

	x	y	u'	v'	nm
Red	0.672	0.328	0.481	0.528	611.3
Green	0.000	1.000	0.000	0.600	
Blue	0.137	0.037	0.173	0.105	464.3

$$\text{Gamma} = 0.443$$
$$U' = 0.7956\,(B' - Y')$$
$$V' = 1.8962\,(R' - Y')$$

	δL^*	δC^*	δH^*	δE^*
Skin tones	−0.47	0.11	3.40	3.55
Low saturation	0.40	−0.70	2.26	3.47
Medium saturation	3.33	0.72	2.01	4.70
High saturation	0.49	−0.87	0.84	2.75
All colours	1.11	−0.27	1.87	3.57

Table B: Primary sets investigated for optimisation (cont.).

Set 10. FCC primaries monochromatic dominant wavelengths.

	x	y	u'	v'	nm
Red	0.672	0.328	0.481	0.528	612.0
Green	0.193	0.782	0.064	0.587	535.0
Blue	0.124	0.058	0.144	0.151	470.0

$$\text{Gamma} = 0.437$$
$$U' = 0.7621\,(B' - Y')$$
$$V' = 1.4433\,(R' - Y')$$

	δL^*	δC^*	δH^*	δE^*
Skin tones	−0.41	−0.45	4.76	5.03
Low saturation	0.36	−0.41	3.67	5.12
Medium saturation	3.89	3.31	3.27	5.68
High saturation	0.19	−2.10	2.80	5.09
All colours	1.14	0.01	3.42	5.24

Set 11. NHK/ATSC HDTV primaries monochromatic dominant wavelengths.

	x	y	u'	v'	nm
Red	0.672	0.328	0.481	0.528	612.0
Green	0.193	0.782	0.064	0.587	535.0
Blue	0.137	0.037	0.173	0.105	464.3

$$\text{Gamma} = 0.439$$
$$U' = 0.7679\,(B' - Y')$$
$$V' = 1.3752\,(R' - Y')$$

	δL^*	δC^*	δH^*	δE^*
Skin tones	−0.40	−0.02	4.62	4.79
Low saturation	0.39	−0.47	2.99	4.28
Medium saturation	3.60	2.02	1.88	4.36
High saturation	0.33	−1.96	1.58	3.57
All colours	1.12	−0.24	2.44	4.13

Table B: Primary sets investigated for optimisation (cont.).

Set 12. First practical spectral compromise set for coverage of Pointer's gamut.

	x	y	u'	v'	nm
Red	0.680	0.320	0.496	0.526	615.1
Green	0.193	0.782	0.064	0.587	535.0
Blue	0.129	0.050	0.154	0.135	468.1

$$\text{Gamma} = 0.438$$
$$U' = 0.7645\,(B' - Y')$$
$$V' = 1.4183\,(R' - Y')$$

	δL^*	δC^*	δH^*	δE^*
Skin tones	−0.41	−0.24	4.72	4.95
Low saturation	0.37	−0.42	3.35	4.77
Medium saturation	3.78	2.81	2.68	6.70
High saturation	7.73	−0.66	2.31	4.44
All colours	3.63	0.39	3.01	5.19

Set 13. Second practical spectral compromise set for coverage of Pointer's gamut.

	x	y	u'	v'	nm
Red	0.680	0.320	0.496	0.526	615.1
Green	0.155	0.806	0.050	0.587	530.0
Blue	0.137	0.037	0.173	0.105	464.3

$$\text{Gamma} = 0.440$$
$$U' = 0.7658\,(B' - Y')$$
$$V' = 1.4968\,(R' - Y')$$

	δL^*	δC^*	δH^*	δE^*
Skin tones	−0.40	−0.05	4.38	4.56
Low saturation	0.57	−0.53	2.14	4.13
Medium saturation	3.54	1.89	2.05	5.40
High saturation	0.37	−1.72	1.47	3.33
All colours	1.17	−0.21	2.19	4.26

Table B: Primary sets investigated for optimisation (cont.).

Set 14. Red and blue taken from Set 3 above, green taken as the dominant wavelength of green taken from Set 8 above (523.2 nm).

	x	y	u'	v'	nm
Red	0.672	0.328	0.481	0.528	611.3
Green	0.100	0.830	0.031	0.586	523.2
Blue	0.137	0.037	0.173	0.105	464.3

$$\text{Gamma} = 0.441$$
$$U' = 0.7489\,(B' - Y')$$
$$V' = 1.6590\,(R' - Y')$$

	δL^*	δC^*	δH^*	δE^*
Skin tones	−0.39	0.07	4.31	4.49
Low saturation	0.68	−0.73	2.89	4.07
Medium saturation	3.46	1.68	2.28	5.20
High saturation	0.40	−1.70	1.45	3.36
All colours	1.19	−0.30	2.43	4.19

Set 15. Green taken from Set 8 above, red and blue monochromatic wavelengths forming a parallel to the line of purples tangential to Pointer's gamut.

	x	y	u'	v'	nm
Red	0.691	0.308	0.520	0.522	620.0
Green	0.000	1.000	0.000	0.600	
Blue	0.144	0.030	0.188	0.087	460.0

$$\text{Gamma} = 0.445$$
$$U' = 0.7988\,(B' - Y')$$
$$V' = 1.8668\,(R' - Y')$$

	δL^*	δC^*	δH^*	δE^*
Skin tones	0.07	−1.47	1.21	1.93
Low saturation	1.01	−0.47	2.03	3.07
Medium saturation	3.85	1.22	2.20	5.20
High saturation	0.96	−2.48	0.96	3.07
All colours	1.62	−0.82	1.61	3.48

Table B: Primary sets investigated for optimisation (cont.).

Set 16. Green at monochromatic dominant wavelength of the green from Set 15 above, red and blue monochromatic wavelengths forming a tangent to Pointer's gamut.

	x	y	u'	v'	nm
Red	0.680	0.320	0.497	0.525	615.0
Green	0.074	0.834	0.023	0.584	520.0
Blue	0.144	0.030	0.188	0.087	460.0

$$\text{Gamma} = 0.442$$
$$U' = 0.7445\,(B' - Y')$$
$$V' = 1.6979\,(R' - Y')$$

	δL^*	δC^*	δH^*	δE^*
Skin tones	0.25	−2.12	1.31	2.53
Low saturation	1.24	−0.91	2.25	3.61
Medium saturation	4.24	2.54	2.40	6.06
High saturation	1.06	−3.88	1.11	4.25
All colours	1.85	−1.14	1.79	4.33

APPENDIX C

Colorimetric Equations

The colorimetric equations used to evaluate the system performances are standard formulae and are included here for completeness.

CIE 1976 chromaticity from CIE 1931 chromaticity

$$u' = 4x/(12y - 2x + 3) \qquad v' = 9y/(12y - 2x + 3)$$

CIE 1931 chromaticity from CIE 1976 chromaticity

$$x = 9u'/(6u' - 16v' + 12) \qquad y = 4v'/(6u' - 16v' + 12)$$

CIE 1976 chromaticity from CIE 1931 tristimuli

$$u' = 4X/(X + 15Y + 3Z) \qquad v' = 9Y/(X + 15Y + 3Z)$$

CIELUV from CIE 1976

$$L^* = 116Y^{1/3} - 16 \qquad u^* = 13L^*(u' - u'_0) \qquad v^* = 13L^*(v' - v'_0)$$

$$C^* = (u^{*2} + v^{*2})^{1/2} \qquad S^* = C^*/L^* \qquad H^* = \tan^{-1}(v^*/u^*)$$

CIELUV differences between colours suffixed 1 and 2

$$\delta L^* = L^*_1 - L^*_2 \qquad \delta C^* = C^*_1 - C^*_2$$

$$\delta E^* = (\delta L^{*2} + \delta u^{*2} + \delta v^{*2})^{1/2} = (\delta L^{*2} + \delta C^{*2} + \delta H^{*2})^{1/2}$$

The CIELUV values relate to visual stimulii, they are psychometric scales. L^* is a lightness or luminance scale running from 0 to 100; it approximately matches a power law of 0.43. C^* is a chroma scale approximating to saturation in television. S^* relates to chromaticity saturation and is actually 13 times the distance of the colour from D65 in the CIE 1976 diagram; it is not a particularly useful value in television. H^* is the hue angle of the colour in the CIE 1976 diagram. H^* and S^* form the polar coordinates of the colour in the CIE 1976 diagram, centred upon D65.

The colorimetric difference formulae relate to visual differences. δL^* is a luminance difference; 2 units are just perceptible. δC^* is a chroma difference relating approximately to saturation; its perceptibility ranges from about 1 unit at D65 to about 5 units at the MAC primaries. δH^* is a hue difference and is not particularly relevant to television measurements. δE^* is a total effect difference; perceptibility ranges from about 1 at D65 to about 5 at the MAC primaries.

APPENDIX D

Colorimetric Performance Tables

Table D1

Colorimetric performance of the constant-luminance coding system when decoded by a conventional decoder.

	Colour specification			Compatible display			Errors		
	Y	u'	v'	Y	u'	v'	δL^*	δC^*	δE^*
1	0.0950	0.2539	0.5027	0.0541	0.2696	0.5055	0.31	−0.85	1.16
2	0.3710	0.2357	0.4931	0.2888	0.2464	0.4952	−0.17	−2.08	2.69
3	0.3000	0.2384	0.4837	0.2194	0.2507	0.4847	−0.36	−1.12	2.18
4	0.2960	0.1839	0.5453	0.2616	0.1769	0.5444	4.21	1.05	5.21
5	0.3010	0.1640	0.4581	0.2507	0.1618	0.4639	2.73	−2.20	6.16
6	0.3010	0.2067	0.4138	0.2148	0.2071	0.3973	−0.82	−0.65	1.26
7	0.1290	0.1804	0.5235	0.0888	0.1756	0.5285	2.48	0.78	2.66
8	0.1900	0.3246	0.4960	0.1487	0.3513	0.5038	1.25	−1.12	2.06
9	0.4410	0.1520	0.5329	0.4655	0.1501	0.5381	6.75	2.09	7.52
10	0.1980	0.1770	0.3658	0.1419	0.1730	0.3468	1.03	−4.57	5.08
11	0.0650	0.3002	0.4882	0.0364	0.3274	0.4943	0.54	0.22	0.59
12	0.2010	0.1471	0.5339	0.1794	0.1466	0.5391	5.53	2.35	6.40
13	0.0630	0.1786	0.3431	0.0348	0.1737	0.3201	0.87	−1.63	2.20
14	0.4260	0.2757	0.5262	0.3737	0.2918	0.5263	1.09	−5.31	5.43
15	0.1980	0.2307	0.3981	0.1272	0.2356	0.3775	−1.09	−0.61	1.67

Table D2

Test colours and compatible display errors.

		Specification			Compatible MAC decoder errors		
		Y	u'	v'	δL^*	δC^*	δE^*
1	White	1.0000	0.1978	0.4683	0.0000	0.0000	0.0000
2	Saturated Blue	0.0466	0.1886	0.2352	−1.7512	4.5946	4.9170
3	Saturated Cyan	0.3314	0.1408	0.4139	−5.1008	14.9973	15.8409
4	Saturated Green	0.3310	0.1357	0.5298	−6.5824	6.5173	9.2630
5	Saturated Yellow	0.7240	0.2093	0.5510	−3.8003	9.9807	10.6797
6	Saturated Orange	0.3181	0.3462	0.5351	−3.0070	9.8636	10.3118
7	Saturated Red	0.1506	0.4212	0.5158	−4.6688	13.4671	14.2535
8	Saturated Pink	0.2373	0.3700	0.4530	−3.2464	10.9190	11.3914
9	Saturated Magenta	0.1283	0.3313	0.3414	2.2598	9.5865	9.8483
10	Desaturated Blue	0.3000	0.1924	0.3969	0.5249	1.7355	1.8132
11	Desaturated Cyan	0.5675	0.1756	0.4573	−1.3967	3.8411	4.0871
12	Desaturated Green	0.4491	0.1771	0.5169	−2.7993	0.4780	2.8398
13	Desaturated Yellow	0.5979	0.2051	0.5358	−2.4569	5.6142	6.1283
14	Desaturated Orange	0.4586	0.2541	0.5154	−0.2049	3.8170	3.8225
15	Desaturated Red	0.1712	0.3213	0.4961	−0.7909	1.4855	1.6829
16	Desaturated Pink	0.1769	0.3068	0.4439	−0.1857	2.5631	2.5698
17	Desaturated Magenta	0.3478	0.2427	0.4063	1.6484	1.0850	1.9735
18	Skin Tone A	0.4404	0.2221	0.4884	0.3748	1.9964	2.0313
19	Skin Tone B	0.3936	0.2246	0.4908	0.3475	2.0488	2.0781
20	Skin Tone C	0.3363	0.2280	0.4997	0.1327	2.2937	2.2976
21	Skin Tone D	0.2124	0.2320	0.5008	0.1374	1.9862	1.9910
22	Skin Tone E	0.1207	0.2397	0.4965	0.2709	1.4857	1.5102
23	Skin Tone F	0.0608	0.2223	0.4889	0.1973	0.8910	0.9126
24	Skin Tone G	0.3305	0.2330	0.4917	0.4422	2.0917	2.1379
25	Skin Tone H	0.2922	0.2376	0.4887	0.5503	1.9559	2.0318
26	Light Foliage	0.2338	0.1813	0.5091	−1.7705	0.4242	1.8206
27	Dark Foliage	0.0656	0.1801	0.4927	−0.9171	0.6453	1.1213

Table D3
HD-MAC channel signals for the test colours.

	Transmission			Compatible MAC decoder			Correct drive signals for MAC system		
	$E'_{Y\mathrm{h}}$	$E'_{U\mathrm{h}}$	$E'_{V\mathrm{h}}$	$E'_{R\mathrm{c}}$	$E'_{G\mathrm{c}}$	$E'_{B\mathrm{c}}$	$E'_{R\mathrm{m}}$	$E'_{G\mathrm{m}}$	$E'_{B\mathrm{m}}$
1	1.000	0.000	0.000	1.000	1.000	1.000	1.000	1.000	1.000
2	0.252	0.268	−0.061	0.186	0.214	0.617	0.218	0.171	0.625
3	0.608	0.152	−0.268	0.319	0.715	0.816	0.044	0.665	0.823
4	0.608	−0.153	−0.200	0.392	0.758	0.400	0.258	0.693	0.361
5	0.865	−0.399	0.062	0.931	0.937	0.320	0.920	0.886	0.028
6	0.597	−0.299	0.368	0.995	0.474	0.189	0.980	0.425	0.008
7	0.427	−0.181	0.378	0.834	0.267	0.180	0.808	0.154	0.160
8	0.523	−0.014	0.412	0.968	0.301	0.504	0.949	0.214	0.518
9	0.397	0.191	0.268	0.686	0.199	0.657	0.690	0.062	0.673
10	0.582	0.172	−0.034	0.545	0.555	0.817	0.556	0.558	0.828
11	0.775	0.045	−0.106	0.661	0.821	0.836	0.637	0.806	0.838
12	0.698	−0.149	−0.068	0.624	0.774	0.495	0.597	0.743	0.466
13	0.793	−0.273	0.040	0.836	0.844	0.421	0.827	0.812	0.351
14	0.704	−0.184	0.193	0.912	0.647	0.453	0.915	0.744	0.427
15	0.452	−0.093	0.252	0.724	0.338	0.325	0.719	0.327	0.322
16	0.459	0.022	0.248	0.726	0.316	0.489	0.727	0.310	0.498
17	0.622	0.147	0.156	0.790	0.497	0.822	0.810	0.514	0.836
18	0.691	−0.071	0.090	0.788	0.661	0.594	0.794	0.665	0.588
19	0.657	−0.076	0.094	0.758	0.626	0.554	0.763	0.630	0.547
20	0.612	−0.098	0.097	0.717	0.585	0.478	0.721	0.586	0.467
21	0.498	−0.084	0.088	0.593	0.472	0.383	0.597	0.473	0.374
22	0.386	−0.059	0.082	0.475	0.356	0.306	0.479	0.359	0.300
23	0.300	−0.032	0.039	0.342	0.287	0.257	0.345	0.288	0.254
24	0.608	−0.076	0.111	0.727	0.567	0.504	0.733	0.572	0.497
25	0.575	−0.065	0.118	0.702	0.527	0.486	0.708	0.534	0.481
26	0.520	−0.092	−0.040	0.476	0.566	0.395	0.460	0.548	0.379
27	0.293	−0.029	−0.027	0.265	0.316	0.254	0.256	0.308	0.250

Appendix D (cont.).

Table D4

Modified compatible signals and resultant colour errors.

	Modified signals				Output			Errors	
	E'_R	E'_G	E'_B	Y	u'	v'	δL^*	δC^*	δE^*
1	1.0000	1.0000	1.0000	1.0000	0.1978	0.4683	0.00	0.00	0.00
2	0.2254	0.1666	0.6172	0.0457	0.1908	0.2360	0.28	1.35	1.38
3	0.1522	0.6737	0.8158	0.3426	0.1425	0.4192	−0.89	3.95	4.05
4	0.2426	0.6830	0.3588	0.3197	0.1348	0.5292	0.92	1.19	1.51
5	0.9313	0.8855	0.1492	0.7299	0.2108	0.5489	−0.28	2.78	2.79
6	0.9784	0.4018	0.1023	0.3051	0.3538	0.5322	1.09	5.15	5.27
7	0.8113	0.1623	0.1611	0.1531	0.4188	0.5161	−0.35	0.58	0.67
8	0.9671	0.1993	0.5044	0.2413	0.3774	0.4572	−0.40	6.96	6.97
9	0.6939	0.1013	0.6574	0.1310	0.3130	0.3502	−0.41	4.50	4.52
10	0.5446	0.5549	0.8169	0.2940	0.1912	0.3981	0.52	1.74	1.81
11	0.6589	0.8023	0.8360	0.5689	0.1786	0.4577	−0.08	3.10	3.10
12	0.6192	0.7324	0.4949	0.4452	0.1820	0.5110	0.26	7.38	7.39
13	0.8364	0.8083	0.3549	0.5967	0.2073	0.5351	0.07	2.47	2.47
14	0.9118	0.6471	0.4527	0.4618	0.2519	0.5119	−0.20	3.82	3.82
15	0.7237	0.3136	0.3251	0.1678	0.3276	0.4938	0.43	3.62	3.65
16	0.7263	0.3065	0.4888	0.1747	0.3093	0.4460	0.27	1.89	1.91
17	0.7900	0.4972	0.8218	0.3271	0.2429	0.4039	1.65	1.09	1.97
18	0.7884	0.6608	0.5943	0.4348	0.2218	0.4864	0.37	2.00	2.03
19	0.7582	0.6261	0.5536	0.3888	0.2242	0.4887	0.35	2.05	2.08
20	0.7169	0.5852	0.4784	0.3346	0.2271	0.4971	0.13	2.29	2.30
21	0.5931	0.4719	0.3832	0.2111	0.2311	0.4982	0.14	1.99	1.99
22	0.4751	0.3564	0.3058	0.1190	0.2393	0.4940	0.27	1.49	1.51
23	0.3423	0.2866	0.2568	0.0679	0.2219	0.4869	0.20	0.89	0.91
24	0.7274	0.5667	0.5039	0.3251	0.2328	0.4894	0.44	2.09	2.14
25	0.7021	0.5274	0.4856	0.2860	0.2377	0.4864	0.55	1.96	2.03
26	0.4765	0.5411	0.3949	0.2323	0.1860	0.5043	0.16	4.91	4.91
27	0.2646	0.3043	0.2543	0.0652	0.1843	0.4897	0.09	2.10	2.11

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